SPINAL CORD DECOMPRESSION SICKNESS AND ITS TREATMENT

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DECLARATION

All the original work described in this thesis was conducted by or under the direct supervision of the author.

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ABSTRACT

Anaesthetised dogs were used in terminal experiments to establish the optimum combination of pressure and oxygen in the delayed treatment of spinal cord decompression sickness (DCS). The DCS was produced by decompressing the dogs in about 5.5 min after a 15 min air dive at 10 bar. Decompression sickness was diagnosed, monitored and quantified using an array of spinal cord evoked potentials (SEP). These were produced by stimulation at three peripheral nerve sites and were recorded simultaneously from three equidistant cord sites. To establish the method studies of the effects of anaesthesia, temperature, treatment gases, time, stimulation and recording variables were undertaken. It was shown that major changes in spinal cord blood flow were required, to cause observable changes in the SEPs. It was shown that cord ischaemia lasting more than 15 minutes reduced the likelihood of SEP recovery after restoration of blood flow. Preliminary studies in the evolution of the model and early comparisons of treatments are described. In the final studies treatment began 15 min after the diagnosis of cord DCS. To find the optimum oxygen pressure 5 groups of 5 dogs were treated with 1.0, 1.5, 2.0, 2.5 or 3.0 bar of oxygen at a total pressure of 5.0 bar. This showed an optimal response in the 2.0 and 2.5 bar groups with 70 and 66 percent recovery after 2 hours of treatment. The lower PO_2 was used in the next study where 3 groups of 5 dogs were treated with 2.0 bar of oxygen at 3.0, 5.0 or 7.0 bar total pressure. A fourth group was given the currently used treatment of 2.8 bar breathing oxygen. There was no statistical difference between the four groups which supported the hypothesis that once beyond a threshold in the region of 3.0 bar no advantage was gained by additional compression. It is proposed that a new treatment using only 2.0 bar of oxygen at 3.0 bar total pressure be tried. While this would probably not alter outcome it would greatly reduce the risks of oxygen toxicity. The form of decompression sickness observed largely supported the venous obstruction model but suggested that autochthonous bubble formation and arterial gas played more than an incidental role.

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ABBREVIATIONS, UNITS, SYMBOLS

AER	auditory evoked responses
AoP	aortic pressure
BP	blood pressure
$\overline{BP}$	mean blood pressure
C	cervical
^{14}C	carbon 14
CAT	computer of average transients
CEP	cortical evoked potential
CSF(P)	cerebrospinal fluid (pressure)
D	diagnosis (as a time point)
DCS	decompression sickness
ECG	electrocardiogram
EEG	electroencephalogram
EP	evoked potential
EVVS	epidural vertebral venous system
f	breathing rate per minute
$F_{ET}CO_2$	percent end tidal CO_2
FFP	far field potential
Hct	haematocrit
HR	heart beats per minute
iv	intravenous
L	lumbar
n	number
P	partial pressure or probability
$PaCO_2$	arterial PCO_2
PP	pulse pressure
RVP	right ventricular pressure
R or Tr	treatment
S	sacral
sc	subcutaneous
SD	standard deviation
SE	standard error of mean
SEP	spinal evoked potential
Sys	systolic
T	thoracic
VER	visual evoked responses
$\bar{x}$	mean

bar	one atmosphere absolute
°C	degree Celsius
ft	foot of seawater (fsw)
gm	gram
h	hour
Hz	cycles per second
iu	international unit
kg	kilogram
m	metre of seawater
min	minute
mg	milligram
ml	millilitre
mm	millimetre
mm Hg	millimetre of mercury
ms	milliseconds

PREFACE

The experiments reported herein were conducted according to the principles set forth in the "Guide for the Care and Use of Laboratory Animals". Institute of Laboratory Animal Resources, National Research Council, DHEW, Pub. No. (NIH) 78-23. The opinions and assertions contained herein are the private ones of the author and are not to be construed as official or reflecting the views of the United States Navy Department or the Naval Service at large.

As the work was conducted in the United States of America the pressure units were necessarily not SI units. Therefore feet of seawater are generally reported but are related to the standard European units as follows:

2 bar (absolute pressure) = 10 metres of seawater = 33 feet of seawater

3 Bar = 20 metres of seawater = 66 feet of seawater

Parts of the work described in this thesis have been or are to be published. The papers are:-

Leitch D R, Hallenbeck J M, Greenbaum L J Jr. The effect of various gases on cortical and spinal somatosensory evoked potentials at pressures up to 10 bar. Aviat Space Environ Med 1983; 54(2): 105-111.

Leitch D R, Hallenbeck J M. A Model of spinal cord dysbarism to study delayed treatment: 1. Producing dysbarism. Aviat Space Environ Med 1984; In press.

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SECTION 1

INTRODUCTION

INTRODUCTION

1.1 GENERAL

For many hundreds of years man has ventured underwater. The duration of his time underwater has only recently increased as breathing appratus was developed to overcome the limitations of breath hold diving. The development of the caisson by Triger in 1839 (1841), for digging in water bearing soils, enabled men to stay long enough at pressure to develop decompression sickness (DCS) when decompressed. The majority of cases of decompression sickness suffer from limb pain. However a significant minority develop varying degrees of neurological impairment. Although Boyle (1670) observed bubbles in a vipers eye and blood when the viper was subjected to reduced presure, it was Bucquoy (1861) who first suggested that the sickness associated with decompression might be the result of dissolved gas coming out of solution. With animal experiments, Paul Bert (1878) demonstrated that nitrogen coming out of solution in blood and tissues, formed the bubbles which caused DCS.

It is believed that Pol and Watelle (1854) first suggested that recompression might be the treatment of choice for DCS. They observed that workers with DCS had discovered that reentering the workings cured their pain. Paul Bert's experiments led him to the same conclusion. Although Smith (1873) who coined the term 'caisson disease' while associated with the building of the Brooklyn Bridge had no idea of the mechanism of DCS, he recommended that a medical treatment lock should be provided. The first such lock was probably that of Sir Ernest Moir during the building of the Hudson River Tunnel in 1893 (Keays, 1909). Certainly by 1895, Snell (1896) was using a medical lock on the Blackwall Tunnel site.

Once the cause of DCS was recognised, pressure became and remains the mainstay of treatment. Pol and Watelle (1854) also considered the advantages of using oxygen as well as pressure. This was resurrected by Bert (1878). However fears of toxicity prevented its introduction and world wide acceptance until the middle of this century. Oxygen is now regarded by many as of equal importance in treatment, as is pressure.

Although there are many standard treatment routines available (Berghage et al., 1978), there have been no properly conducted assessments of the factors of pressure and oxygen in treatment. The standard treatments are based on little experimental evidence and mostly on empirical applications of theoretical concepts (Barnard, 1978). Early treatment of spinal cord DCS is usually effective and problem free, but delay in treatment leads to poor recovery (Rivera, 1964; Slark, 1965).

The purpose of this project was to look at the problem of delayed treatment of spinal cord DCS. The first objective was to find the lowest effective PO_2 for use at a fixed absolute pressure. The second objective was then to vary absolute pressure around the established optimum PO_2 and discover whether increasing pressure beyond a presumed threshold improved the outcome of treatment. To achieve these goals an animal model of cord DCS which lent itself to delayed treatment was required. Clinical assessment of the preparations would not be possible so development of a quantifiable electro-physiological method was needed. Somatosensory averaged evoked potentials from peripheral nerves were expected to enable the spinal cord to be interrogated and to allow some degree of lesion localisation. The electrophysiological method would have to be validated by testing the effects on it of many variables, including spinal cord blood flow.

1.2 PRESENTATION OF DECOMPRESSION SICKNESS

The multitude of alternative terms used to describe DCS, compressed air illness or caisson disease gives some indication of the extent of its possible symptoms and signs. There are graphic terms such as bends and niggles which describe pain, and hits, chokes and staggers used to describe more serious forms of DCS. The compressed air working fraternity are responsible for giving us the Type I, Type II classification for mild and serious DCS. The diving fraternity generally differentiates between mild and serious DCS. Serious DCS being mostly neurological in origin but also including cardiopulmonary DCS or "chokes".

Approximately 10 - 35% of those cases of DCS which come to active treatment will show some signs of central nervous system involvement

(Rivera, 1964; Slark, 1965). Rarely will the cases exclusively show only central nervous system involvement. About one third of cases with musculo-skeletal DCS will also exhibit central nervous system problems. In addition, other systems may commonly be involved (Slark, 1965).

These cases present the most difficult treatment problems and significant numbers will never achieve a complete cure inspite of all known treatments. It is to these cases that all further discussion will be confined.

Prodromal indications of neurological decompression sickness may include pain in conjunction with cardiopulmonary and constitutional upset. This can take the form of a cardiopulmonary embarrassment known as the "chokes", which may progress to clinical shock. The prelude can simply be a severe disproportionate fatigue leading to peripheral vasoconstriction, nausea, sweating, hypertension and malaise.

The "chokes" are a triad of signs and symptoms. There is a burning substernal pain of increasing severity. At first, it may only be apparent on coughing, but it progresses to frank inspiratory and expiratory pain. A cough, intermittent at first and readily provoked by smoking, develops into uncontrollable paroxysms. There is progressive dyspnoea and respiratory distress. The cause is presumed to be the combined effect of gaseous embolisation of the pulmonary artery, and the release, in the lung, of smooth muscle active substances causing vasoconstriction leading to pulmonary oedema, and possibly bronchoconstriction (Chryssanthou et al., 1970).

The ensuing shock with which the "chokes" is sometimes associated may be due to a combination of mechanisms, such as a loss of vascular tone due to cord involvement, myocardial depression from hypoxaemia and acidosis, pulmonary embolisation and hypovolaemia. The hypovolaemia probably results from a widespread increase in capillary permeability and cell sludging, leading to loss of plasma water and an increased haematocrit (Cockett and Nakamura, 1964a, b).

As DCS is caused largely by vascular obstruction consequent on

random 'in situ' bubble formation within the vascular system, neurological decompression sickness presentation is unpredictable. Where or how the peripheral nervous system is involved remains unknown, so it is safer to assume that all nervous system involvement is central in origin. Because of its comparatively tenuous blood supply, the spinal cord is the most frequent area afflicted (Woollam and Miller,1958).

Aviators frequently suffer cerebral lesions presenting in any number of ways, but commonly as migraine-like headaches with visual disturbances, and occasional hemiparesis (Fryer and Roxburgh, 1965).

Spinal lesions are more common in divers, presenting classically as regional sensory disturbances, paraplegia and bladder paralysis with urine retention and faecal incontinance. Less commonly, trunk pain may also indicate cord involvement.

These various forms of DCS tend to develop rapidly after the offending decompression, and because of the dominantly vascular nature of the disease, the first aid and subsequent treatment lends itself to measures of circulatory support and restriction of coagulability, in addition to the necessary oxygen and recompression for the removal of the root cause.

The complexity and duration of very severe cases can be seen in the following example:

> An "experienced" professional diver carried out an energetic wreck survey in about 180 ft (55 m) of water. After 25 minutes, he surfaced directly. While getting another diving set ready to go in order to complete his task, he developed shoulder pain which disappeared when he dived again. After another 20 minutes, he again surfaced directly, but was so fatigued that he had to be lifted into the boat for transport to the nearby ship in order to undergo surface decompression. On his way across the deck to the chamber, within 5 - 10 minutes of surfacing, he became unsteady and had to be assisted into the chamber. They continued with the surface decompression table and during the initial decompression to 40 feet the diver became aphasic, lost the coordination

of both arms and developed severe tremor in both legs. During several unorthodox treatment manoeuvres before expert help was was summoned, he twice lost consciousness and also briefly, lost the sight in one eye. After the subsequent stormy therapy using pressure, oxygen, drugs and fluids, he was left with an almost complete paraplegia, various sensory deficits, mostly below T_8, although one arm was patchily involved; asymmetric weakness of both forearms and hands, a paralysed bladder and faecal incontinence Subsequent intensive rehabilitation enabled him to walk without aid after 8 months. Bladder control returned within 8 weeks and he even regained the capacity for sexual intercourse, although there was some residual sensory deficit.

Usually neurological DCS will be preceded by musculo-skeletal pain, "chokes", general malaise, or any combination of these. It is generally stated that a high proportion of "chokes" will go on to neurological DCS (Heller et al., 1900; Behnke and Shaw, 1937; Hallenbeck et al., 1975).

The onset of these serious forms of DCS, tends to be more rapid than for pain only bends. A detailed series of cases monitored by Kidd and Elliott (1975) had all the neurological cases presenting within about 90 minutes of surfacing, while pain only cases continued to occur for up to 15 hours.

A recurrent problem is one of failure to diagnose neurological DCS, because in its more subtle forms, it is less apparent than the very obvious severe joint pain in the milder form of DCS. There is often some functional power loss associated with severe pain and the differentiation between the two problems is never easy, even with experience. There is thus a risk of overlooking what is in fact the main problem and consequently undertreating it. From such situations arise complicated and hard to treat cases of serious DCS.

Slark (1965) in a retrospective survey of cases treated by the Royal Navy, suggests that his apportioning of serious cases into categories, may in fact, be an underestimate of their frequency for this very reason. In addition, many cases are seen and treated by medically unskilled personnel, so that their reporting is naturally less than satisfactory.

The diversity of sites for bubble formation and damage in all tissues renders the symptomatology protean (Rivera, 1964), it may also be multifocal and is always unpredictable. Unlike aviators, the spinal cord is the site of most neurological DCS in divers, although occasional cerebral presentations do occur.

A summary of perhaps the three best known surveys of DCS in divers is given in Table 1. These leave no doubt that the neurological cases are dominated by cord lesions, but that a good number of cases involve cranial nerves and their end organs, brain stem and cerebrum.

The infinite number of possible sites for bubble lodgement in the brain results in many possible manifestations of cerebral DCS, among them: behavioural disorders (moodiness, change of affect, upset judgement/psychoses), visual blurring, diplopia (cranial nerve), scotomata, hemianopia, fortification spectra, migrainous headaches (usually in those with a history of migraine), speech disorders, through to unconsciousness and frank convulsions (Rivera, 1964).

The development of cord lesions is often insidious and the slowly evolving paraesthesia and slight limb weakness can be masked by localized pain or the "chokes", until well advanced. Pins and needles may be felt in the feet which later feel wooly and cold. The progress may be slow or fast and lead to paraplegia with loss of bladder and sphincter control. Several different cord segments may be afflicted at once giving patchy neurological deficits, sometimes also showing as a unilateral loss. The lower extremities are more commonly affected than the arms. Lesions may not be strictly segmental and cases of glove and stocking sensory deficit have been seen.

Back, chest and abdominal girdle pain often are indicators of a cord problem. Previous conditions or injuries may predispose to the onset and even dictate the site of the lesions. The author has seen two cases where the site of cord DCS was associated with an old prolapsed intervertebral disc. Kidd and Elliot (1975) recorded a case associated with the site of a cord root injury sustained during a prior lumbar puncture.

TABLE 1

DISTRIBUTION OF SIGNS AND SYMPTOMS IN SERIOUS DECOMPRESSION SICKNESS

Rivera (1964) Percentage of all cases surveyed (n = 935)	
Numbness/Paraesthesia	21.2
Muscular Weakness	20.6
Paralysis	6.1
Urinary Disturbance	2.5
Muscular Twitching	1.2
Incoordination	0.9
Dizziness/Vertigo	8.5
Nausea/Vomiting	7.9
Visual Disturbance	6.8
Headache	3.9
Unconsciousness	2.7
Personality Change	1.6
Agitation/Restlessness	1.3
Convulsion	1.1
Equilibrium Disturbances	0.7
Auditory	0.3
Cranial Nerves	0.2
Aphasia	0.2
Dyspnoea	2.0
Fatigue	1.2

Slark (1965) Percentage of all case surveyed (n = 137)	
Disorder of Sensation	8.0
Disorder of Power	11.0
Vertigo	4.4
Nausea/Vomiting	5.1
Visual Disorder	2.2
Headache	3.6
Unconsciousness	2.9
Shock	5.8

Kidd and Elliott (1975) Percentage serious cases only (n = 250+)	
Sensory Impairment	25
Motor Impairment	13
Dizziness	19
Nausea/Vomiting	5
Visual Disorder	10
Confusion/Disorientation	14
Dysarthria	3
Dyspnoea/Coughing	17

The high proportion of cerebral cases seen in follow up by Rozsahegyi (1959) and Peters et al. (1977) and some of the bizarre findings attributed to cord lesions suggest that there may be a higher incidence of cerebral occurrences in divers than is generally believed. It is not easy to explain glove and stocking sensory loss through a spinal cord lesion; the possibility of more peripheral lesions seems less feasible than the probability of a more central problem.

Follow up surveys may well be biased towards what authors think they are going to show. Cases with residual problems may well be easier to find and probably more willing to participate than those without evident problems. So necessarily, these cases may come from the most

severely, acutely affected group and this may well explain the high proportion of cerebral problems. This line of reasoning may be more clear after consideration of the pathological mechanisms of the disease.

1.3 MECHANISMS OF NEUROLOGICAL DECOMPRESSION SICKNESS

The basic cause of DCS is bubble formation. The exact site of their initial development remains unknown. On the basis of Guyton and Coleman's (1968) view that interstitial fluid pressure and intralymphatic pressure are slightly lower than ambient pressure at one atmosphere, these regions would be reasonable sites for bubble nucleation. Certainly, ultrasonic monitoring indicates that the first circulating bubbles are usually detected in the venous rather than the arterial circulation (Spencer et al., 1975).

The bubbles cause mechanical disruption and vascular obstruction, but they also set in train a series of far reaching pathological reactions through the surface activity at the blood-gas interface.

The surface activity results from the interface generated electrokinetic forces distorting the circulating globular proteins. Ordinarily, these proteins are oriented so that the hydrophobic part is on the inside of the molecule and the hydrophilic part is in aqueous blood. The blood-gas interface causes this configuration to be altered so that the hydrophobic part points across the interface into the gas of the bubble (Lee and Hairston, 1971). Enzyme activation or protein denaturation may then occur. The Hageman factor is activated and active sites on enzymes may be exposed. These events can lead to some proteins becoming lyophobic and causing RBC clumping and the adherence, release and aggregation of platelets (Hallenbeck, et al., 1973).

Fat emboli develop from the coalescence of intravascular lipid and intravasation of depot fat (Bergentz, 1971). Reduction of blood flow rates in the microvasculature, results in decreased blood shear strain rates which effectively increase intracapillary pressure. This in turn induces vascular fluid loss into the tissues. The consequent haemoconcentration generates a vicious circle, which with time becomes increasingly difficult to break, as fibrinogen concentration increases

and cell agglutination occurs. Substances released by bubble formation cause increased capillary permeability causing further fluid loss. If the process is sufficiently widespread, venous return declines and so, in its turn, does cardiac output. The process rapidly shows as a marked increase in haematocrit which may easily exceed 50 percent (Hallenbeck et al., 1975b).

The mechanisms are tightly interlocked and many other substances are released and activated including vasoactive amines, kinins and complement. The resultant hastening of coagulation in the area of stasis leads to fibrin deposition which reinforces the vascular obstruction started by the platelet and red blood cell aggregates and bubbles. The resulting local ischaemia causes prostaglandins to be released, which in the same way compound the problem further (Hallenbeck and Anderson 1982).

Post mortem examination of the cord in dogs has shown the resulting neurological lesions to be largely confined to the white matter (Hallenbeck et al., 1976). The lesions were usually found in the thoracic and lumbosacral regions but also occasionally in the cervical region. No lesions were found in the brain. The infarctions showed only small perivascular haemorrhages and this with the grey matter sparing, is indicative of venous not arterial obstruction (Henson and Parsons, 1967).

Studies of the cords of goats which have dived gave similar findings with lesions mainly in the white matter at the watershed of the arterial supply, adjacent to the grey matter (Palmer et al., 1978). The main area affected was the cervical region. Interestingly, a large portion of those with lesions had never been treated for, nor shown signs of neurological involvement. Again no lesions were found in the brain.

The possibility of extravascular bubbles in the cord remains. These were observed by Boycott et al., (1908) in goat cords but not by Catchpole and Gersh (1947). Hills and James (1982) expound a model of extravascular bubbles in the cord as the main mechanism in cord DCS.

It had long been thought that the cord damage was the result of

arterial embolisation with bubbles (Catchpole and Gersh, 1947), but the evidence against this is now strong. In embolic phenomena, the brain is the main target organ and in one large survey of neurological vascular disease no cases of cord embolisation were found (Blackwood, 1958).

This is not surprising when it is considered that the human brain constitutes about 98% of the CNS (Truex and Carpenter, 1969) and receives 75 to 85 times more blood flow than the cord (Kety, 1960). In divers it is largely the cord which is affected by DCS while arterial gas embolism affects the brain. Although both have their origins in vascular bubble formation the mechanisms of their selection of a target organ are clearly different.

Some understanding of the cord vasculature sheds light upon the mechanism of cord DCS. According to Batson (1940), the epidural vertebral venous system (EVVS) in man is a large, valveless plexiform lake. It is connected at each intervertebral foramen with ascending lumbar veins in the abdomen, with azygos and hemiazygos veins in the thorax, and with the vertebral veins in the neck. The EVVS also communicates with cranial dural sinuses via ventral occipital sinuses and with posterior bronchial and parietal pleural veins. The direction of flow in the EVVS changes frequently in response to respiratory and intracavity pressure changes. Radicular veins drain cord blood into the EVVS, and like the arterial supply it is nonsegmental and rather tenuous (Woollam and Miller, 1958). Clemens (1970) states that the volume of the system is some 20 times greater than the arterial supply to the region, so that only about 5% of the EVVS blood volume needs to be flowing at any one time.

The EVVS thus differs from other veins in that it is not just a unidirectional duct returning blood towards the heart, but more an almost stagnant pool with an ordinarily sluggish flow which frequently changes direction. So it becomes apparent that any obstruction to its flow may rapidly proceed into the sequence of coagulation previously described.

The situation has been clarified using a dog model of cord DCS (Hallenbeck, 1976). The dog EVVS is less complex than man's, being

basically a pair of venous trunks extending from skull to sacrum within the spinal column. It joins the cranial dural sinuses and anastomoses with the azygos and hemiazygos veins (Miller et al., 1964).

Some of these studies have shown that bubbles and the products of blood-gas interface activity form peripherally and return to the lungs via the heart (Chrysanthou et al., 1970). So called 'silent bubbles' (they do not appear to cause DCS) have been detected enroute to the lungs by using ultrasonics (Spencer et al., 1975). This gives rise to the conclusion that the lungs can dispose of and remove bubbles and it is known that they can inactivate many of the products of the bubble surface activity (Fishman and Pietra, 1974a, b). However, if the bubble assault becomes too large, the lung mechanisms will be overwhelmed; vascular obstruction will occur causing a rise in pulmonary artery pressure and in turn, of central venous pressure. This is thought to be reflected back into the EVVS so reducing its blood flow. The EVVS already has a small flow rate so that bubbles simultaneously forming in it will tend to grow and coalesce. The venous back pressure will bring about stasis in the EVVS so encouraging the bubble growth process to the point of obstruction (Hallenbeck, 1976). If the stasis lasts longer than the silicon clotting time, the coagulation process will be initiated and vascular fluid loss begin (Botti and Ratnoff, 1964).

In dogs decompressed from a deep dive there was, generally within 20 minutes a rise in right ventricular pressure associated with some respiratory distress indicating bubble embolisation of the pulmonary artery. This was usually followed immediately by a rise in CSF pressure indicating the pressure rise in the EVVS transmitted from the pulmonary circulation. Signs of neurological deficit immediately followed this. A few cases of cord lesions were seen without the preceding cardio-pulmonary changes indicating the possibility that EVVS bubbles alone may cause the obstructions (Hallenbeck, 1976). These findings may explain why not all clinical cases seen experience the pulmonary disturbances often described.

Once the haemostatic process has been initiated, fibrin is laid down and consolidation of the obstruction begins. The resulting ischaemic

damage initiates the mechanisms implicated in the no-reflow phenomenon (Hallenbeck and Furlow, 1978). It can be seen that prompt treatment is essential to avoid permanent damage.

This mechanism cannot necessarily be invoked to explain the occasional episodes of cranial involvement with the brains'more secure anastomotic circulation. Inevitably, venous outflow must be reduced, but in a generalised not a focal way. However, as the brain is a frequent target of arterial embolic episodes, it seems possible that a sufficiently great rise in pulmonary artery pressure could open up arteriovenous shunts allowing bubbles to embolise cerebral end arteries where they may grow in the resulting vascular stasis.

The question of extravascular bubbles remains, and in occasional cases these are a possible explanation for cases such as that described by Kidd and Elliott (19759.

1.4 RESIDUAL PROBLEMS

Case surveys clearly show that delay between onset and treatment decreases the likelihood of complete recovery and frequently complicates the treatment (Rivera, 1964; Slark, 1965; Kidd and Elliott, 1975). The reasons for this must be self evident from the understanding of the mechanism. Rivera (1964) observed that onsets within 15 minutes of surfacing tended to have more residual defects. This is presumed to be because the earlier the onset, the more severe the case.

While following up tunnel workers treated for neurological DCS Rozsahegyi (1959) found that after 2.5 - 5.5 years, many of them had significant neurological disturbances, even among a number who had been sign and symptom free on completion of the compression therapy. Those who were not completely free of problems within 6 weeks of treatment were likely to have problems for several years at least. Of those who suffered with problems only 4% were completely clear after 2.5 years. Progress over the first 6 months can be good but thereafter small improvements may continue for several years although complete recovery is highly unlikely. Rozsahegyi also reported some sequelae of late onset.

A contribution to the problem of the late sequelae may be the failure to make a correct judgement as to the seriousness of a case when it presents for treatment. Sequelae most commonly seen are varying degrees of sensory and motor loss sometimes with bladder control and impotency problems; occasionally there may be various cerebral changes.

1.5. AN HISTORICAL VIEW OF TREATMENT

By the end of the nineteenth century recompression was firmly established as the treatment for DCS. What was not clear then, no more is it now, was to what pressures should patients be taken for optimal effect. At the Blackwall Tunnel Snells' (1896) general policy was to recompress to the depth of relief and not to exceed working pressure. Time at treatment pressure was up to 30 minutes.

Keays (1909) recommended returning to working pressure. Although many cases recovered at lower pressures, there was a high recurrence rate if the higher pressure was not used. Using only two thirds of the working pressure with a wait of up to 60 minutes was recommended by Ryan (1912).

Yarborough and Behnke (1939a)summarised US Navy experiences and the available treatment options around a discussion of Boyles Law, as recompression to:

a. Pressure of relief
b. Pressure of relief plus an arbitrary amount
c. Pressure of the causative dive
d. Pressure greater than the pressure of the causative dive.

Behnke and Shaw (1937) demonstrated that 3 bar (66 ft, 20 m) was adequate to stop the cardiopulmonary DCS arising in dogs after long dives at 5.4 bar. Breathing air did not however prevent recurrences. Yarborough and Behnke (1939a) practised recompression to depth of relief plus one bar. They developed guidelines within a minimum pressure of 4 bar (100 ft, 30 m) and a maximum pressure of 6 bar (165 ft, 50 m). They also set a minimum time at maximum pressure of 30 minutes. They observed "that those patients who respondto pressure treatment, do

so rather promptly". The approach to those with a poor response was empirical in "that as long a improvement occurs the maximum pressure should be maintained for a period of at least 2 hours". They modified their Haldanian type decompression to use oxygen from 2.8 bar (60 ft, 18 m) back to the surface. In the event of recurrence they recompressed to the depth of relief which was invariably less than 3 bar and stayed 12 to 24 hours.

These treatment practices had about a 50 percent recurrence, as did modified versions (Yarborough and Behnke, 1939b). Van der Aue et al. (1945) produced treatment outlines embodying the Yarborough and Behnke principles in formal tables. For neurological DCS these required compression to an arbitrary pressure of 6 bar (165 ft, 50 m). These were highly effective until the number of delayed treatments increased with the advent of sports diving (Rivera, 1963).

The earlier Behnke and Shaw (1937) experiments with dogs treated at 3 bar had included a group which breathed oxygen. On return to the surface they did not have a recurrence of cardiopulmonary problems as had their air breathing counterparts, thus demonstrating the advantages of oxygen in gas clearance. However, the result was not a success as some dogs went on to develop cord lesions while at 3 bar. It was for this reason that deeper compression was recommended with oxygen breathing during some of the decompression.

Driven by the falling success rate of the Van der Aue tables, Goodman and Workman (1965) introduced the minimal pressure oxygen compression therapies used at 2.8 bar (60 ft, 18 m). These tables were very successful and increased the success rate from about 45 percent to 65 percent (Bornmann, 1967). They form the first choice in treatment throughout the world today.

The use of oxygen at such high partial pressures is not without hazard. Sustained exposure to 2.8 bar of oxygen causes cerebral oxygen toxicity. The problem is largely avoided by breathing oxygen for a series of 20 minute periods broken by 5 minute periods breathing air. This stemmed from experimental observations by Kaufman et al. (1956)

who showed that the time to convulsion in guinea pigs could be extended by a factor of three if they intermittently breathed air. It is the author's experience that although oxygen convulsions during treatment are not common, when they do occur, the often prolonged post-ictal phase greatly complicates treatment. If 2.8 bar of oxygen was shown to be more than adequate for treatment then it would be wise to use a lesser but equally effective oxygen tension. Some groups actually use oxygen at a higher pressure for shorter periods, Hart (1974) reports successful treatment of DCS with continuous oxygen breathing beginning with 30 minutes at 3.0 bar followed by 60 minutes at 2.5 bar before decompression. Ballantine (1979) has reported central cord necrosis in rats exposed to 3.0 bar of oxygen for 5 hours. He suggested that it probably occurs between 2.5 and 5 hours. It has been demonstrated that high levels of oxygen cause vasoconstriction in the CNS (Ledingham, 1977). Intuitively this must be a disadvantage in treating a disease believed to be largely the result of impaired perfusion.

The most commonly used pressures for treating DCS arising as a result of air diving are 2.8, 4.0 and 6.0 bar. The available range of tables extends to 8.0 bar for the Royal Navy and 10.7 bar in Russia (Berghage et al.,1978). There is little published experimental work to justify these higher pressures, but Barnard (1978) cites Russian experiments purporting to show that increasing the maximum treatment pressure increased the effectiveness of treatment in animals with severe DCS. This is contrary to his own work (Barnard and Hanson, 1973). Mice dived in oxyhelium to depths between 125 m and 225 m were decompressed and then recompressed after a short interval to six depths between 0 m and 80 m. They showed that irrespective of the depth of the dive there appeared to be an optimal treatment pressure of between 2.5 and 5.0 bar, although they considered the real upper limit to be 3.5 bar. Similarly in studies into the optimal pressure for treating cerebral arterial gas embolism no improvement in recovery was seen at pressures above 2.8 bar (Leitch et al., 1984).

1.6 THE RATIONALE OF TREATMENT

It is generally believed that most decompressions result in some bubble formation, but that their numbers and size are small so they remain 'silent'. Barring the fortuitous location of a bubble or bubbles

in a sensitive and vulnerable tissue, DCS occurs when an undefined tolerable dose is exceeded (Spencer et al., 1975). Therefore once DCS presents, the first objective is to stop further bubble growth. The manifestations of DCS arise either because of mechanical disruption or as a result of ischaemia. Breathing oxygen, even at one bar, should slow bubble growth and possibly even reverse it by increasing the inert gas gradient. In addition tissue oxygenation should be improved. This is a standard first aid measure. As fluid loss from the intravascular space occurs in serious cases fluid replacement is required to prevent the less treatable processes such as coagulation and vascular stasis. Plasma has been used (Barnard et al., 1966) and low molecular weight dextrans were popular until recently. Now it is generally believed that crystalloid solutions such as lactated Ringers or Hartmanns may be preferable (Davis, 1979). The principal treatment is pressure, preferably with a raised PO_2. Given adequate time bubbles should be cleared. In cases which do not wholly recover at pressure it is impossible to define what is adequate time. This problem has given rise to the saturation therapy where non-responding cases are held for many hours in air or oxynitrogen mixes at pressures usually between 2.8 and 4.0 bar (Miller et al., 1978). This is an increasingly used alternative to the option previously used, of just going deeper. There are several problems with going deeper. Using air causes increased narcosis. The PO_2 rises so that pulmonary oxygen toxicity will have an earlier onset which can only be prevented by using nitrogen or helium for further pressurisation. As soon as you start to control the PO_2 you need a chamber equipped for saturation. You only go deeper with very ill patients and by doing so you get further away from help. The final problem is the return to the surface without causing a recurrence or a new problem. Such decompressions are generally slow. The whole is further complicated by the possibility of oedema. The treatment of cerebral oedema has been reviewed by Pierce and Jacobson (1977). Dexamethasone is widely used to counter vasogenic oedema but its efficiency is much debated (Rap and Dabrowiecki, 1978; Ito et al., 1980). The antioedema effects of hyperbaric oxygen are clearly beneficial (Miller, 1963). In times of crisis mannitol or glycerol have been used.

Where cases arrive at surface pressure with notable neurological deficits, it has been the author's and others practice to repeat hyperbaric

oxygen therapies up to twice a day. This is only continued as long as improvements, even if only transient, are associated with the treatments. While clearly hastening recovery it remains unknown whether the final outcome is improved.

A purely theoretical approach applying Boyles Law to bubbles gives some indication of the relative merits of pressure in treatment. Volume is inversely related to pressure, so every doubling of pressure halves volume as shown in Table 2. However:-

$$\text{Diameter} = \sqrt[3]{\frac{6V}{\pi}}$$

therefore while volume may be halved diameter is not. Much of the problem created by spherical bubbles can be attributed to their linear dimension rather than their volume where disruption and obstruction are concerned. Table 2 illustrates how the effects of increasing compression on spherical bubble dimension has quite a small effect in diameter compared with that on volume, and quickly enters the realms of diminishing returns. When cylindrical bubbles are compressed they reduce in length first until they become spherical thus the volume reduction is most effective.

Compressing a spherical bubble to 50 m (6 bar) will reduce volume to one sixth (17%) and diameter to 55 percent. The reduction in radius will increase the surface tension forces thus further raising bubble PN_2 above tissue PN_2 causing an outward diffusion gradient. Oxygen partial pressure using air will increase to 1.2 bar, so improving oxygenation. The raised PN_2 will cause generalised increased inert gas uptake which creates a further risk on decompression. This, with the raised PO_2 puts a limit on the holding time at pressure. There has to be a balance between how much pulmonary oxygen toxicity can be permitted to develop while still allowing time for safe decompression to a pressure where oxygen will no longer be a problem. While at 50 m there is the problem of nitrogen narcosis which impairs mental performance and the problem of easy access to the patient.

Haemoglobin is effectively saturated while breathing air and plasma carries 0.31 ml of oxygen per 100 ml of whole blood. About 20 ml of

TABLE 2

THE EFFECT OF COMPRESSION ON BUBBLE SIZE

PRESSURE	DEPTH		VOLUME	DIAMETER
(bar)	(metre)	(feet)	(percent)	(percent
1	0	0	100	100
2	10	33	50	79
3	20	66	33	69
4	30	99	25	63
5	40	132	20	58
6	50	165	17	55
7	60	198	14	52
8	70	231	12	50
9	80	264	11	48
10	90	297	10	46

oxygen is carried in 100 ml of arterial blood. Mixed venous blood carries about 14 ml at rest so the mean resting tissue requirement is about 6 ml per 100 ml of blood. The effect of pressure on oxygen carried in saturation in blood (per 100 ml) is:

	BREATHING GAS	
PRESSURE	AIR	OXYGEN
1 bar	0.3	2.0 ml
2 bar	0.8	4.5 ml
3 bar	1.3	6.5 ml

Therefore at 3 bar breathing oxygen, tissue requirements can be met from oxygen in solution. A minor drawback to this is the loss of haemoglobin buffering. However the length of the diffusion pathway into hypoxic tissue is greatly increased so that survival of larger volumes of ischaemic tissue is possible.

Applying the standard oxygen treatment to a spherical bubble with compression to 2.8 bar will theoretically reduce bubble volume to 36 percent and diameter to 71 percent. The absence of inert gas greatly increases the nitrogen gradient so accelerating the outward diffusion of nitrogen. The vasoconstriction reduces intracranial and therefore spinal canal pressure and oedema is reduced (Miller, 1973). The major disadvantage is oxygen toxicity.

Kunkle and Beckman (1983) calculated that the rate of bubble clearance should be the same with air at 6.0 bar as with oxygen at 2.8 bar. The added advantages are the increased availability of oxygen, the accessibility of the patient, and the reduced decompression risk associated with treatment lasting about one seventh of the time of the standard air table in uncomplicated cases.

The French try to get the best of both approaches as suggested by Behnke and Shaw (1937) with a middle range compression to 4 bar (30 m) and breathing oxygen rich mixtures (50 percent)(Berghage et al., 1978).

1.7 CASE EXPERIENCE

At the start of this study the author had cause to conduct a three year review of treatment experience in the Royal Navy (Leitch, 1979). A large number of cases came from civilian sources. There were 27 cases of serious DCS. Of these 20 presented within one hour of surfacing, one within 6 hours, one later than 6 hours and there were 5 unknown intervals. The time delay between onset and treatment was less than one hour in 2 cases, 1 to 5 hours in 11 cases, 5 to 10 hours in 6 cases, 10 to 24 hours in 7 cases and one later than 24 hours. Twenty one cases were treated with oxygen at 2.8 bar. This included an untreated case of spontaneous recovery which later relapsed. Once at pressure 43 percent were cured by 10 minutes, 57 percent by 45 minutes and 67 percent by the time they surfaced. One case relapsed, 5 surfaced with mild symptoms and 2 with signs. Four of these received extra oxygen at pressure. Six cases were treated with air. Only 3 surfaced sign and symptom free and all 6 treatments were complicated.

The effect of delay before treatment was well demonstrated. Of those treated within 5 hours, 44 percent were cured by 10 minutes, 78 percent by 45 minutes and 78 percent by the time of surfacing. This compared with 20, 20 and 50 percent respectively in cases where treatment was delayed more than 5 hours. Four cases which were unable to walk on surfacing were given up to 9 additional one hour oxygen treatments at 2 bar. By 8 months all were able to walk unaided.

1.8 EVOKED POTENTIALS

Spinal evoked potentials (SEP) and cortical evoked potentials (CEP) are being increasingly used experimentally, diagnostically, and for monitoring in neurosurgical procedures (Grossman, 1979). Dawson (1946-7) discovered that if recordings of EEGs were time-locked to a peripheral nerve stimulus, then the random signals were averaged out by self-cancelling, leaving the time-locked evoked potential. The same principle can be applied to electrospinograms.

For the proposed studies of the treatment of spinal cord DCS a system permitting remote interrogation of the neuraxis was required. It also needed to be able to localise lesions to the major cord divisions.

Design constraints required that the model be controlled and maintained remotely in a pressurised chamber for periods of up to 5 hours. A chamber containing an animal, once pressurised, cannot be easily decompressed and opened without putting the experiment at risk; not even in the brief period when it is near atmospheric pressure between the first dive and the treatment. In addition, the neuraxis and its integument could not be invaded, as such procedures might predispose to localised DCS (Kidd and Elliot, 1975). The development of lesions resulting from DCS is often rapid (Rivera, 1964; Hallenbeck et al, 1975a; Leitch, 1979) so it was imperative that each interrogation and recording be short, in order that the onset times of DCS be known within narrow limits, and the degree of severity be known before treatment.

The selected inputs were left and right peroneal nerve, usual roots in the dog L_6, L_7, S_1, S_2), left tenth or eleventh intercostal nerve, and left median nerve (usual roots C_8, T_1, T_2) (Hoerlein, 1978). The evoked potentials (EP) were recorded at segments L_1 or L_2, T_8 or T_9, C_7 or C_8, and right somatosensory cortex. This arrangement would permit localisation to five broad regions, lumbar, caudal thoracic, rostral thoracic and caudal cervical cords, and the cortical and intervening regions. Interest lay largely in the first two and last cord regions, which experience showed to be the most common sites for DCS lesions.

SECTION 2

METHOD

METHOD

2.1 OVERVIEW

This study progressed through a series of developmental steps towards the two ultimate goals. These were to study the relative merits of oxygen and pressure in the treatment of spinal cord DCS. Therefore the parts of the method common to all experiments, studies of the method and some particular details are described below. Minor variations and experimental plans relating to each stage are described in relation to the relevant study in the results sections.

2.2 BASIC MATERIALS AND SUPPORT

Adult male mongrel dogs weighing between 7 and 21 kg were used in these investigations. Studies were terminated with the intracardiac injection of saturated potassium chloride. The dogs were sedated with xylazine (1.1 mg kg^{-1} s.c.) and atropine (0.05 mg kg^{-1} s.c.). They were then anaesthetised with sodium pentobarbital (13.5 mg kg^{-1} i.v.) and maintained on a routine of half the initial dose after 20 minutes and a maintenance dose of 4 mg kg^{-1} h^{-1} given in divided doses at 20 minute intervals. Small adjustments to the maintenance regimen were made if required. After intubation, ventilation was maintained with a modified Bird® Mark 7 respirator. A catheter was placed in the left forepaw cephalic vein for anaesthesia maintenance and infusions. When preparation for physiological monitoring was complete the dogs were placed prone in a rigid head-holding stand, modelled after a stereotaxic frame, and secured by ear bars. Rectal temperature was continuously recorded and maintained between 37.5 and 39.0°C by means of a hot water circulating plate incorporated into the base of the head-holding stand.

2.3 PHYSIOLOGICAL MONITORING

Left and right femoral arteries were catheterized with polyethylene tubing (OD 2.42 mm) for respectively arterial pressure (AoP) monitoring and blood sampling. A 7F gauge preformed catheter (Becton-Dickinson No. 9423) filled with heparinized saline (2 i.u. ml^{-1}) was advanced

from the right femoral vein to the right ventrical for pressure (RVP) measurement. Pressures were measured using vented Gould Statham P23 1D physiological transducers with matching transducer amplifiers and recorded on a Gould recorder (Model 2800). A five-lead ECG harness was connected (4 limb leads and V5) and a Lead II recording made continuously. A urinary catheter was inserted into the bladder and connected to a collection bag. A fluid balance chart was maintained. Early in the preparation the haematocrit was checked. All dogs with a haematocrit below 35% were rejected. All dogs with a haematocrit above 47% were given normal saline or lactated Ringers solution sufficient to drop the haematocrit to 42%. This was to correct any dehydration. If the fluid was surplus then it was cleared and the haematocrit rose again by the time the control period was reached. The urine bag was emptied at the end of the control period.

Once the dog was placed in the stand, the skull was exposed by reflecting skin, muscle, and periosteum over the right somatosensory cortex. Skin from over the distal part of the nasal bones was also excised. The skull and nasal bones were drilled into cancellous bone. The holes were filled with electrode gel and a pair of stainless steel electrodes inserted. A two lead EEG was recorded from these on the Gould recorder after being amplified and filtered (1 - 30 Hz) by a Gould Universal amplifier.

When preparation was complete the dog and stand were moved into the compression chamber (Bethlehem Corporation Size 1.68 x 0.76 m) and all connections made. The heating plate was connected to a hard piped hot water system supplied from outside the chamber. End tidal CO_2 was continuously monitored by a Beckman LB2 CO_2 analyser, and maintained at 3.0 to 4.5 percent of surface equivalent by altering cycle time and inspiratory flow rate. The ventilator could also be manually operated from outside the chamber. Pentobarbital anaesthesia was provided through a port in the chamber wall, connected to the forepaw venous line. The right arterial line was connected to another port so that blood samples could be drawn when the chamber was pressurised. After the electrophysiological system described below was tested a needle was inserted percutaneously into the cisterna magna, and connected to another transducer for the measurement of cerebrospinal fluid pressure (CSFP).

Arterial blood samples were taken at intervals during preparation and control periods for blood gas, pH and haematocrit measurements. Samples were also taken during DCS and its subsequent treatment. Haematocrit rises and pH falls were corrected by infusion of lactated Ringers solution and 8 percent bicarbonate solution

2.4 AUTORADIOGRAPHIC BLOOD FLOW STUDIES

The dogs used in this study had an additional catheter placed distally into the right femoral artery so that when the proximal and distal catheters were connected through a Y-connector, the leg arterial circulation was externalized, permitting rapid sampling during the autoradiographic blood flow study. When the one minute ^{14}C-iodoantipyrine autoradiographic blood flow study was required, 50 μCi kg^{-1} of ^{14}C-iodoantipyrine was infused at a constant rate through the forepaw venous catheter over a one minute period while arterial blood was serially sampled every 4-6 seconds. The cardiac arrest that terminated this procedure was produced by the injection of saturated potassium chloride into the right ventricle. The brain, spinal cord and heart were then removed, frozen in liquid freon suspended over liquid nitrogen and cut into 20-micron sections. The tissue concentration of the isotope was determined autoradiographically.

The spinal cord was divided approximately at the electrode sites into four gross segments, and up to 24 sections were taken at intervals from each gross segment. The sections were laid on standard X-ray film and incubated for several days. The films were then processed and the images analysed by densitometry to derive the tissue isotope concentration. Local blood flow was calculated from the following formula:

$$C_i(T) = \lambda k_i \int_o^T C_a e^{-k_i (T-t)} dt$$

where $C_i(T)$ = the concentration of tracer substance in the tissue at time T; λ = the tissue-blood partition coefficient for the tracer material (approximated as 1); k_i = the rate of blood flow per unit weight of tissue multiplied by the reciprocal of the partition coefficient for that tissue; and C_a = the concentration of trace substance in the arterial blood (Reivich et al., 1969).

2.5 EVOKED POTENTIAL MEASUREMENT

The CEPs were recorded by tapping the EEG signal. The SEPs were recorded from an array of spinal electrodes. Pairs of insulated 1 mm diameter stainless steel wire electrodes were introduced percutaneously into the interspinous space at about L_1, T_8, and C_7. They were hammered into the spinal lamina of adjacent vertebrae until their points were securely embedded. Impedance of the cortical and spinal electrodes was less than 2 and 6 kohms respectively.

Stimulating electrodes were pairs of 20 guage stainless steel needles carried on double banana plugs and secured with heat shrink plastic. The peroneal nerve electrodes were curved down and inserted percutaneously astride the neck of the fibula where the peroneal nerve was palpable. The median nerve electrodes were inserted with the cathode proximal on the medial aspect of the distal end of the humerus where the median nerve was palpable. The intercostal nerve electrodes were inserted astride the 11th rib from its inferior aspect. The electrode holders were secured to the skin by safety pins. Stimuli of 100 - 140 V (3 x motor threshold) with a duration of 0.3 ms and a current of 10 mA was given at a rate not exceeding 2.5 s^{-1}.

The stimulator (Grass S88) and two Nicolet Computers of Average Transients (CAT) (Models 1074 and 1072) were driven by a Nicolet Stimulus Pulse Generator (NIC-502). The stimulus was delivered through a Grass Photoelectric Stimulus Isolation and Constant Current Unit (PISU 6C) and directed through a four-way switching box on the outside of the chamber. The output from the three spinal and the cortical sites was averaged simultaneously (n = 128) on the two CATs; the three SEPs by the 1074 with a 26 - 30 ms span, and the CEP by the 1072 with a 110 ms span. The outputs were observed on two Tektronix oscilloscopes (5110) and recorded on three Hewlett-Packard X-Y plotters (HP 7045 A and B). On leaving the chamber through a CONAX high pressure penetrator, the signals went to differential amplifiers (NIC-200A) (gain 10^4) before being further amplified (gain 40) and filtered on a 30-3000 Hz bandpass (NIC-501 A). The cortical signal was split at this point for the EEG and CEP output. Each output was calibrated with a 50 μV and 20 ms square wave signal derived from a Nicolet calibrator (NIC CAL-100).

Latencies were measured from the start of the stimulus and all peak to peak amplitudes were derived from peak deviation from a baseline.

2.6 ELECTRODES

Reusable cortical electrodes were made from stainless steel slotted OH sheet metal screws (size no. 4 length 19 mm) by drilling a 1.02 x 7.00mm hole down the shaft from the centre slot. The connectors were gold plated copper-beryllium alloy pins (1.02 x 8.00mm - AMPinc 205089-1).

The reusable spinal electrodes were made in lengths of 8.0 and 6.5 cm from stainless steel orthopaedic finger wires (0.89 x 127 mm - C - wires Concept Inc.). The point was given a longer tapered bevel and the whole was coarse sanded before a pin connector (as above) was soldered to the cut end. The junction was sheathed in heat shrink plastic. The entire electrode except the pin was dipped in clear polyurethane to give three or four coats before baking for 48 hr at 110°C. Testing of the insulation revealed infinite resistance up to 500 V. Two millimetres of the tip were bared and the end was lightly sanded to allow easy passage through tissues. Routine maintenance was ultrasonic cleaning and resharpening.

The thoracic electrodes were prone to noise of two origins, muscle noise and ECG artifact. Good earthing and accurate and deep electrode placement were the only solutions short of neuromuscular blockade and synchronising the measurement cycle with the ECG cycle.

All electrode cables were Malco Microdot 75 ohm "Mini-Noise" coaxial cable (275-3801-0000) which were led through the high pressure penetrator in the chamber wall. The electrode connections were made through 5 cm of multistrand flexible copper wire ending in the matching connectors. This arrangement permitted thoracic ventilation movement without working the electrodes free. All screens came to a common earth.

2.7 EVOKED POTENTIAL PROCESSING

Up to five control sets of evoked potentials were collected from each peripheral nerve input before the start of any experiment. The EPs were recorded with the positive up convention and with a 2 ms delay

before stimulation. Figure 1 shows the form of peroneal and median CEPs with three principal waves - P_1, N_1 and P_2 - relating to near-field cortical potentials. In addition, as many as 11 far-field potentials (FFP) relating to subcortical events were observed between the stimulus and P_2. The observed mean latencies for P_1, N_1 and P_2 in the comparable group of 11 dogs, from the median nerve were 10.2, 15.9 and 26.8 ms respectively, and from the peroneal nerve, 14.0, 20.9 and 31.8 ms. The SEPs (Fig. 2) produced complex polyphasic wave forms giving up to 10 easily identifiable pairs of peaks. The more rostral to the stimulus was the recording, the longer the latency, the greater the spread, and the smaller the amplitude. Records from close to the root input were dominated by a large negative wave and a later slow positive wave at 8 - 10 ms.

Analysis of these records took two forms. The CEPs were measured primarily for P_1N_1 amplitude. The OP_1 and N_1P_2 amplitudes were also measured as were the latencies of the primary peaks and the FFPs. Spinal evoked potential records were also measured for the principal peak-to-peak amplitude and for the amplitude of the late slow positive wave. Initially, this was done by hand but eventually each trace was marked for the peaks of interest and given an arbitrary baseline to compensate for occasional wandering slow voltage changes. They were then entered into a computer (PDP 11-70) using an Elographics Digitizer (Model E241 with an Orthoplex Coordinator Sensor Type 3825-1). Latency change was of minor importance compared with amplitude so that the emphasis was on the latter measurement. A simple numerical description of a record was needed for statistical purposes and pilot studies showed that fine discrimination techniques were not required for the gross changes that occurred. An effective means of describing each SEP as a single value was found to be the simple summing of peak-to-peak amplitudes (P_1N_1 + N_1P_2 + P_2N_2 etc.). The mean of the designated control values was then calculated and all subsequent values were normalized by expressing them as a percent of control. As a falling amplitude was sometimes associated with an increasing peak-to-peak latency, it was thought that sensitivity, would be increased by dividing the summed amplitude by peak-to-peak latency. This was feasible so long as all peaks remained visible. However, it contributed nothing to the overall results beyond

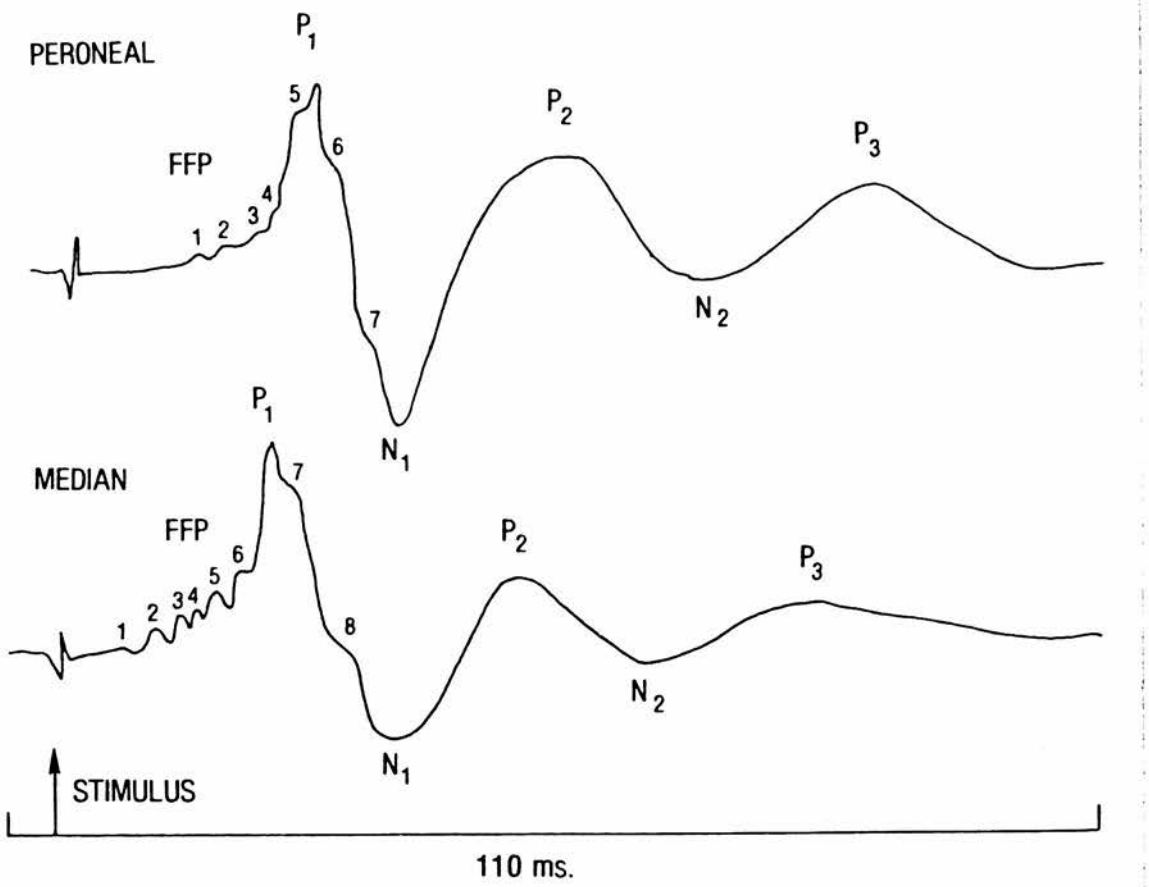


Figure 1. Representative cortical evoked potentials. The principal cortical peaks are marked P_1, N_1 etc., and the far-field potentials are marked 1 - 8.

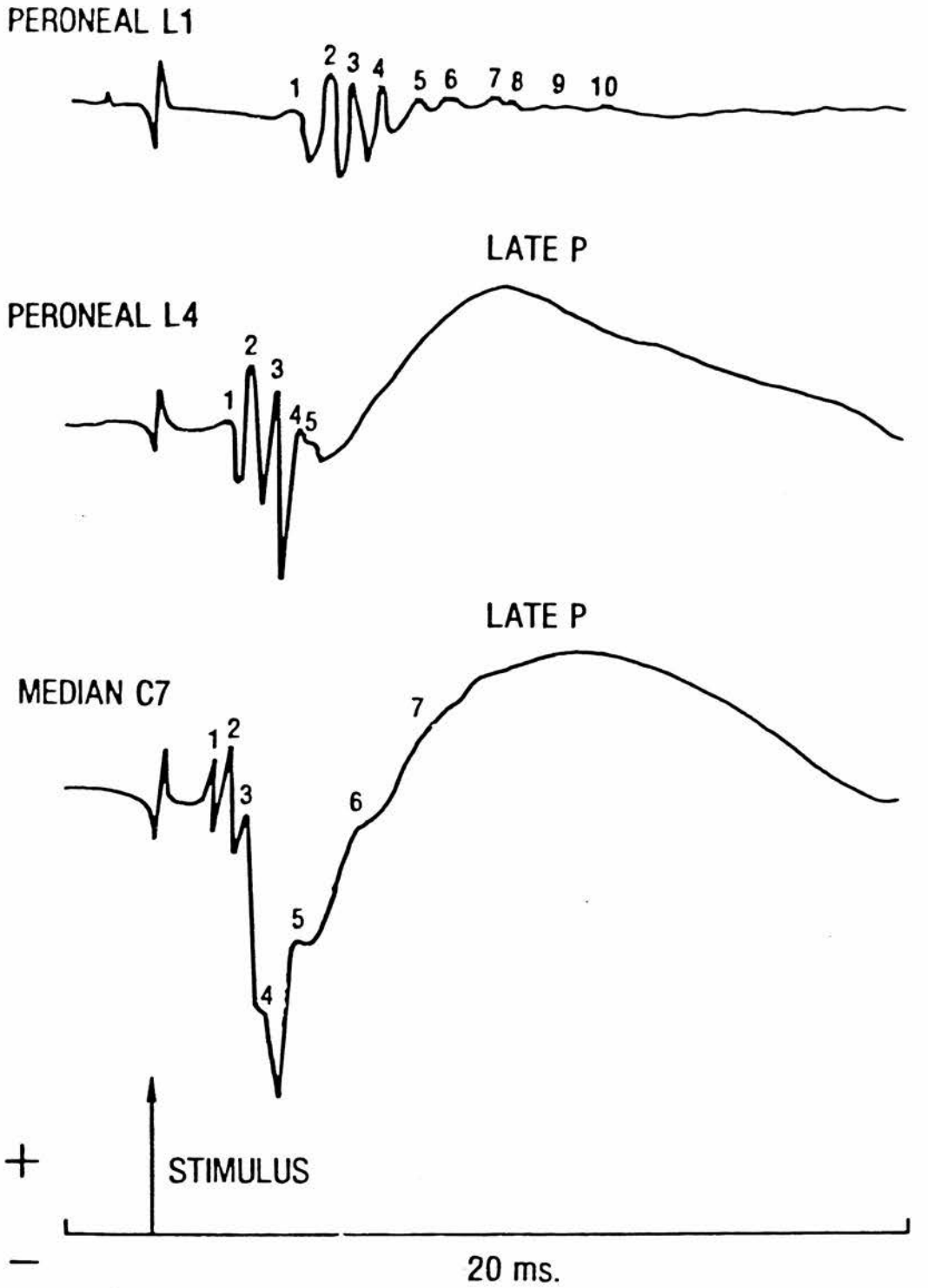


Figure 2. Representative spinal evoked potential. The records are labelled with stimulus and recording site. The numerals are placed by the positive peaks considered relevant. The succeeding negative peaks would have the same number.

the knowledge that latency shifts were also being considered, because amplitude generally was markedly reduced before latency shifts occurred. This analytic technique was therefore abandoned and cumulative peak-to-peak amplitude retained as the index of measurement.

2.8 STIMULUS FREQUENCY AND DURATION

There was no change in SEP form, latency or amplitude at stimulus rates up to 5 Hz in eight dogs. In the range 5 - 8 Hz there was a slight tendency for the late slow P wave ($\sim$ 8 ms) to lose amplitude while the principal early waves remained unchanged.

Fourteen dogs were tested at rates 0.9, 1.9, 2.9 and 3.9 Hz in a randomised sequence with 2-3 CEP records to median nerve stimulation made at each rate. Six dogs were anaesthetised with pentobarbital and the remainder with chloralose. There was no difference between the anaesthetic groups. There was a significant loss of amplitude when the rate exceeded 2.9 Hz ($P < 0.01$) but no significant change in latency, although P_1 latency did tend to increase (Table 3). For all other studies the stimulus rate used was between 2.0 and 2.5 Hz.

The optimal stimulus duration was found to be 0.3 ms which produced a larger amplitude than shorter times but did not lead to distortion of early waves by the stimulus artifact.

TABLE 3

THE EFFECT OF STIMULUS RATE ON CORTICAL EVOKES POTENTIAL (x ± SE N = 14)

		FREQUENCY (Hz)			
		0.9	1.9	2.9	3.9
P_1 Latency (ms)		13.8 ± 0.36	14.0 ± 0.41	14.3 ± 0.40	14.4 ± 0.39
N_1 Latency (ms)		28.0 ± 2.96	29.2 ± 3.11	28.7 ± 2.30	28.6 ± 1.76
Amplitude as Percent of 0.9 Hz value	OP_1	100	105.5 ± 3.47	101.2 ± 2.53	90.4 ± 2.79
	P_1N_1	100	103.4 ± 2.87	97.6 ± 3.32	86.3 ± 3.95
	N_1P_2	100	103.3 ± 5.87	96.6 ± 7.55	71.1 ± 5.82

2.9 SIGNAL FILTERING

Reducing the bandpass -3db points from 1-8000 Hz to 30-3000 Hz had a pronounced effect on CEP amplitude but little effect on latency. The combined effect of narrowed band pass and indifferent electrode position can be seen in comparing Chlor (1) 30-3000 Hz and nasal reference with Chlor (2) 1-8000 Hz and frontal sinus reference in Table 4 and 5 (amplitude) and Figures 3 and 4 (voltage effect).

Studies on eight dogs showed that there was little apparent difference between a 8000 and 3000 Hz limit except for the reduction of high frequency noise. Reducing the limit to 1500 Hz blunted all peaks in the SEPs and FFPs.

Changing the lower limit from 1 to 5 Hz had little effect but moving it to 30 Hz caused a profound drop in amplitude. In the CEP, OP_1, and P_1N_1 were reduced 45 and 20% respectively. However, this did clarify the presence of P_2 which was otherwise barely identifiable.

The effects on SEP waves were less impressive and were most noticeable in the later slow positive wave. There was a small reduction in peak amplitude as a result of dropping the top limit from 8000 to 3000 Hz.

2.10 ANAESTHESIA

Prior to this study the maintenance regimen for pentobarbital or ∝-chloralose anaesthesia was guided by indications of a lightening plane of anaesthesia. Any regimen which depended on shifting planes of anaesthesia could well have a variable effect upon evoked potentials (Pimmel et al., 1976; Parker, 1978a; Arezzo et al., 1979) but might also destroy an experiment through undue movement should an animal become light. There were practical problems over infusing large volumes of ∝-chloralose from outside a chamber pressurised to as much as 10 bar. Anaesthesia by continuous infusion would also have been a problem. Pentobarbital was chosen for the chamber studies for this reason.

A retrospective analysis of the anaesthetic regimens of 24 dogs used in other studies showed that with an initial pentobarbital dose of 12.5 mg kg^{-1} (iv) the intervals for the maintenance dose of 25 mg

TABLE 4

SOMATOSENSORY CORTICAL EVOKED POTENTIALS: PEAK TO PEAK AMPLITUDE - EFFECT OF VOLTAGE ANAESTHESIA AND METHOD.

PENTO - Pentobarbitol 4 mg kg^{-1} hr^{-1} - Bandpass 30-3000 Hz - Nasal Reference
CHLOR (1) - α-Chloralose 40 mg kg^{-1} hr^{-1} - Bandpass 30-3000 Hz - Nasal Reference
CHLOR (2) - α-Chloralose 40 mg kg^{-1} hr^{-1} - Bandpass 1-8000 Hz - Frontal Sinus Reference

Peaks	Condition	N=10	Stimulus voltage 20	40	60	80	100	120	140	Amplitude in µV at 140 V
OP_1	PENTO	$\bar{x}$ (%)	6.6	60.0	81.6	90.1	91.2	97.2	100	39.2
		± 95%	-0.7-13.9	38.1-81.9	67.2-96.0	80.7-99.5	79.6-102.8	89.4-105.0	-	28.0-57.4
	CHLOR(1)	$\bar{x}$ (%)	5.3	57.8	75.3	83.9	90.1	96.9	100	78.2
		± 95%	-1.2-11.8	39.2-76.4	63.8-86.8	74.6-93.2	82.9-97.3	92.7-101.1	-	60.0-96.4
	CHLOR(2)	$\bar{x}$ (%)	-	11.7	36.5	57.8	74.6	89.7	100	147.7
		± 95%	-	5.8-17.6	29.5-43.6	47.9-67.8	64.2-85.0	83.6-95.8	-	116.6-178.8
P_1N_1	PENTO	$\bar{x}$ (%)	4.4	56.8	87.5	91.5	96.8	98.9	100	72.7
		± 95%	-0.3-9.1	36.6-77.0	74.3-100.7	85.6-97.4	89.8-103.8	94.1-103.7	-	40.7-104.7
	CHLOR(1)	$\bar{x}$ (%)	4.7	55.5	74.1	82.7	91.0	96.5	100	170.1
		± 95%	-1.4-10.8	38.7-72.3	62.7-85.5	72.9-92.5	84.2-97.8	91.6-101.4	-	116.0-224.2
	CHLOR(2)	$\bar{x}$ (%)	-	17.0	39.6	56.0	66.0	83.5	100	226.2
		± 95%	-	5.8-29.3	25.6-53.6	44.5-67.5	54.2-77.8	76.0-90.9	-	151.6-300.8
N_1P_2	PENTO	$\bar{x}$ (%)	3.5	53.0	83.2	84.4	91.7	95.8	100	48.7
		± 95%	0.6-6.4	30.6-75.4	67.3-99.1	76.4-92.4	82.2-101.2	90.4-101.2	-	29.4-68.0
	CHLOR(1)	$\bar{x}$ (%)	3.9	58.4	81.1	87.0	96.1	98.0	100	137.0
		± 95%	-1.2-9.0	42.2-75.6	65.0-97.2	73.1-100.9	83.2-109.0	91.2-104.8	-	71.6-202.4

TABLE 5

SOMATOSENSORY CORTICAL EVOKED POTENTIAL: PEAK LATENCY - EFFECT OF VOLTAGE, ANAESTHESIA AND METHOD

PENTO - Pentobarbital 4 mg kg^{-1} hr^{-1} - Bandpass 30-3000 Hz - Nasal Reference
CHLOR(1) - ∝-Chloralose 40 mg kg^{-1} hr^{-1} - Bandpass 30-3000 Hz - Nasal Reference
CHLOR(2) - ∝-Chloralose 40 mg kg^{-1} hr^{-1} - Bandpass 1-8000 Hz - Frontal Sinus Reference

Peak	Condition	n=10	Stimulus Voltage 20	40	60	80	100	120	140
P_1	PENTO	$\bar{x}$(ms)	18.9	13.7	13.3	13.3	13.3	13.3	13.3
		± 95%	15.1-22.7	12.4-15.0	12.5-14.1	12.5-14.1	12.3-14.3	12.3-14.3	12.3-14.3
	CHLOR(1)	$\bar{x}$(ms)	15.0	14.4	14.1	13.8	13.7	13.6	13.6
		± 95%	13.1-16.9	13.3-15.5	13.1-15.1	12.9-14.7	12.8-14.6	12.7-14.5	12.7-14.5
	CHLOR(2)	$\bar{x}$(ms)	-	22.4	16.4	14.9	14.3	14.2	14.0
		± 95%	-	17.2-27.6	14.3-18.5	13.3-16.5	12.8-15.8	12.8-15.6	12.7-15.3
N_1	PENTO	$\bar{x}$(ms)	32.1	21.6	20.3	20.0	20.0	19.9	20.0
		± 95%	25.7-28.5	19.4-23.8	19.0-21.6	18.6-21.4	18.5-21.5	18.5-21.3	18.5-21.5
	CHLOR(1)	$\bar{x}$(ms)	30.0	25.9	23.9	23.5	23.2	22.6	22.4
		± 95%	25.4-34.6	22.6-29.2	21.1-26.7	20.9-26.1	20.5-25.9	20.3-24.9	20.1-24.7
	CHLOR(2)	$\bar{x}$(ms)	-	53.2	38.9	33.9	28.9	27.0	25.4
		± 95%	-	37.7-68.7	34.0-43.8	29.0-38.8	24.0-33.8	22.5-31.5	22.8-28.0
P_2	PENTO	$\bar{x}$(ms)	44.7	35.6	33.9	34.0	34.2	33.7	34.0
		± 95%	40.2-49.2	32.8-28.4	31.3-36.5	31.3-36.7	31.6-36.8	31.1-36.3	30.7-37.3
	CHLOR(1)	$\bar{x}$(ms)	53.3	45.4	43.8	43.4	43.4	43.4	43.0
		± 95%	35.7-70.9	37.9-52.9	36.5-51.1	35.9-50.9	35.7-51.1	35.5-51.3	34.7-51.3

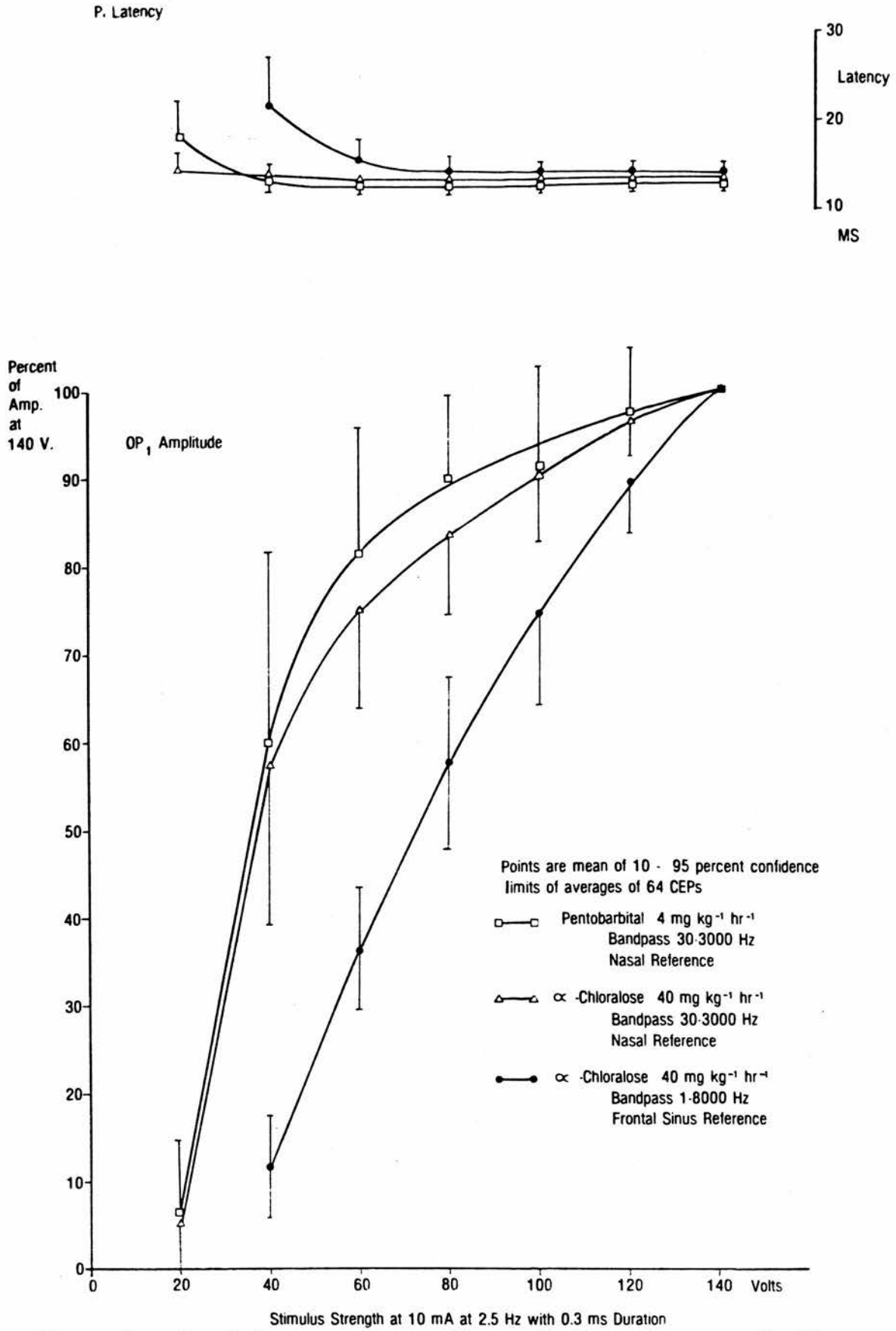


Figure 3. The influence of recording method and two anaesthetics on somatosensory cortical evoked potentials: P_1 latency and OP_1 amplitude.

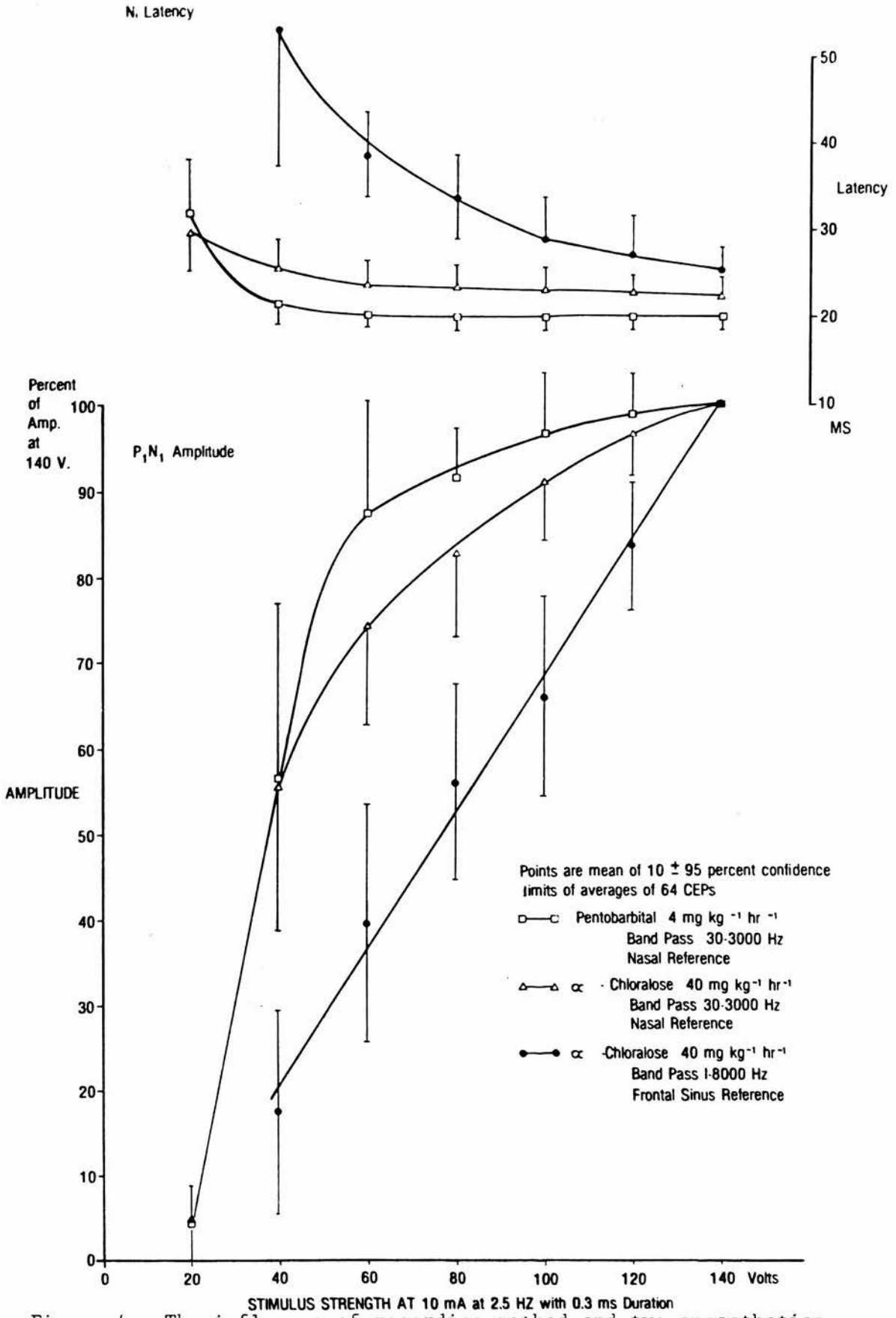


Figure 4. The influence of recording method and two anaesthetics on somatosensory cortical evoked potentials: N_1 latency and P_1N_1 amplitude.

varied between 1 and 155 minutes. Plotting the cumulative anaesthesia given to each dog, showed that the dose required in unit time was linear after about 40 minutes and was much less than the amount given during the first 40 minutes. The mean interval between doses after 40 minutes was 22 minutes. The dose-time slope was 4 mg kg^{-1} hr^{-1}. To arrive at the 40 minute point the initial dose was increased to 13.5 mg kg^{-1} and half that dose was repeated at 20 minutes, being injected slowly and diluted with saline. The maintenance dose was then given at 20 minute intervals unless two successive 20 minute checks failed to elicit a corneal reflex, then a dose was withheld. By the time the dog was placed in the chamber it was usually clear whether or not the maintenance dose should be changed. A need to deviate from this schedule was uncommon.

In six dogs studied over 5 hr, the direction of change of SEP and CEP P_1N_1 amplitude was observed from both median and peroneal nerve stimulation, with relationship to maintenance doses of pentobarbital. There was no clear indication that EPs decreased following anaesthesia or increased during pre-anaesthesia intervals. Only the late slow positive wave at 8 ms in the median-cervical SEP showed a tendency to decrease after pentobarbital ($P < 0.05$ chi-square).

The margin of safety with pentobarbital was seen when two dogs, on completion of other experiments, were given increasing doses at shorter intervals. Blood pressure remained depressed when the dose reached 16 mg kg^{-1} hr^{-1}; at this point EEG amplitude also fell. Peroneal CEP only lost amplitude when the dose reached 33 mg kg^{-1} hr^{-1}.

The comparison of CEPs obtained under the two anaesthetics showed that those recorded under pentobarbital had 50 to 60% less amplitude than those recorded under chloralose (Table 4). However, with increasing stimulus strength, an asymptote was approached earlier with pentobarbital.

2.11 STIMULUS VOLTAGE AND ANAESTHESIA

Ten dogs were studied under each anaesthetic regimen at the start of various experiments. Stimulus voltage was varied in 20 V steps between 20 and 140 V in either ascending or descending sequence. The CEP from

from the median nerve input was recorded. The latencies of P_1, N_1, P_2 and the peak-to-peak amplitudes were measured. The results are presented in Table 4 and 5 as "Pento" and "Chlor (1)", and Figs. 3 and 4.

By 60-80 V the latency was fixed under pentobarbital and the peak-to-peak amplitudes exceeded 90% of the maximum obtained at 140 V. Under both regimens the visible motor threshold was between 30 and 40 V although SEP and CEP were clearly identifiable before then. A reasonable working voltage where the response was asymptotic and the latency fixed would be about three times motor threshold at 100 to 120 V. Recording without a stimulus or by stimulating the tip of the tail resulted in essentially flat recordings except for the stimulus artifact in the latter.

Median and peroneal CEP and SEP at the three sites were recorded in a further seven dogs to see how SEP amplitude and CEP related under pentobarbital anaesthesia. The amplitude grew proportionally in both SEP and CEP, the best relationship being between the early (3 - 6 ms) lumbar SEP waves and the peroneal CEP. The same applied for the comparable waves (1 - 4 ms) with the median - cervical SEP and CEP.

All SEP waves were usually present by 60 V and in only 3/13 cases did SEP continue to increase when CEP was maximal. It was not possible to identify one particular SEP wave as being associated with the CEP primary waves. The SEP waves had a fixed latency within ± 0.1 ms by 80 V, this coincided with the presence and fixed latency of all the cortical FFPs in most series. With the exception of the occasionally observed first SEP wave (standing wave) which had a fixed latency at all spinal sites, and the same latency as the earliest cortical FFP, no temporal coincidence between the SEP waves and the cortical FFPS was seen.

2.12 CORTICAL ELECTRODE POSITIONS

Prior to this work the placing of the active electrode for median CEP had been to go 10 mm lateral to the bregma (Fig. 5) and just behind the coronal suture. This led too frequently to repositioning of the

electrodes, and was of course no use in the occasional dog which had no visible suture lines.

Prospectively, dogs were studied by taking the measurements shown in Figure 5 designated as - IB, BN, BL, and LE. As both peroneal and median CEPs were to be studied, BL had to be less than 10 mm in order to move between median and peroneal areas. Control EPs were recorded and on completion of the experiment, a needle dipped in indian ink was pushed through the inner table of the skull into the brain. The vault of the skull was cut, and before removal, was photographed from a fixed position. The bone was then removed and the meninges cleared so that a second photograph could be taken of the underlying brain. Where brain marking was unsuccessful the overlaying of the two photographs allowed the location of the electrode to be fixed with reference to the sensory cortex in the post-central gyrus (Hamuy et al., 1956). Ten dogs with equally good median and peroneal CEPs were selected to find the best measurement system. In these mongrel dogs, weighing 9 - 17 kg, the ratio of IB + BN to IB + LE was 2.97 ± 0.07 (SE), about one third of the PA distance between inion and nasal bones. In larger dogs with extensive frontal sinuses, it was necessary to go less than that distance in practice. The lateral measurment (BL) proved satisfactory at 6 to 7 mm.

Initially, the indifferent electrode was placed in the frontal sinus but increasing the distance between the two electrodes enhanced the cortically recorded FFPs. Placing the indifferent electrode near the anterior end of the nasal bones reveals the FFPs but at a cost of about 10% decrement in amplitude of the CEP. The effect of this, in addition to the decrement caused by the narrowed bandpass, is shown in Chlor (2) in Tables 4 and 5, and in Figures 3 and 4. The fixed subcortical origins of the FFPs are demonstrated in Figure 6 where simultaneous bilateral CEP recordings were made. The FFPs have the same latencies on both sides indicating volume conduction from a fixed point. The earliest FFP is the only one sometimes also seen in the SEP records. The remainder clearly have their origin between the cervical recording site and the cortex.

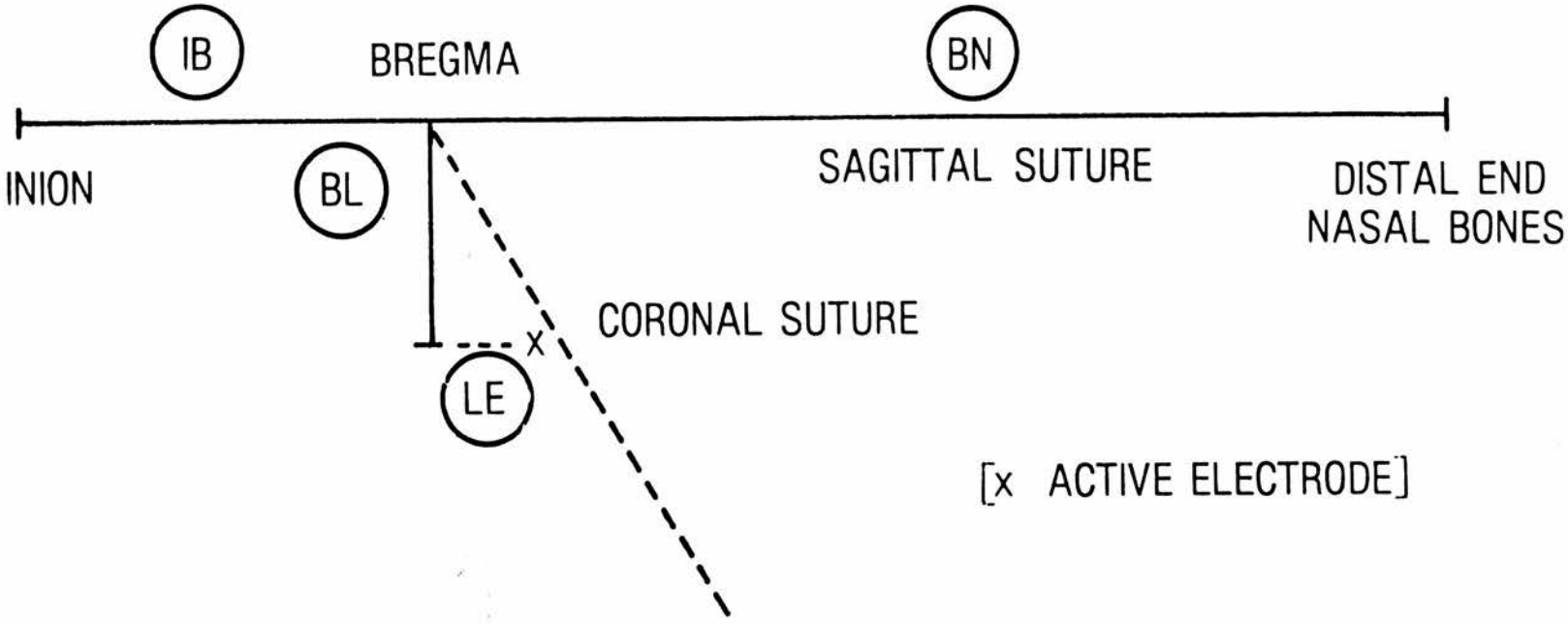


Figure 5. Measurement points for cortical electrode siting.

IB - Inion - Bregma distance
BN - Bregma - Nasal Bones distance
BL - Bregma - Lateral line of active electrode
LE - Anterior displacement of active electrode from BL.

2.13 SPINAL ELECTRODE POSITIONS

Several electrode types and arrays were tried before adopting the steel wires placed into the posterior spinal arch as pairs in adjacent interspinous spaces. Examples of the SEP obtained from this bipolar configuration are given in Figures 7 and 8. The recordings around the relevant root entry zones were dominated by the large negative and late slow positive intermediary potentials. As the recording site moved rostrally these faded to leave the axonal volleys or travelling waves which gradually lost amplitude and increased in latency.

Replacing the indifferent electrodes with a common reference removed much of the fine detail in the polyphasic waveform but greatly increased the amplitude of some of the remaining waves. Increasing the distance between the monopolar electrode and the reference electrode, increased the noise and made recording susceptible to ECG breakthrough which would have necessitated tying the stimulus to a silent point in the ECG cycle.

Electrodes placed in the posterior spinous processes produced SEPs of smaller amplitude. The amplitude was related to distance from the cord. When studying left and right peroneal nerve inputs there was an impression that electrode placement away from the mid-line could be detected by the difference in SEP amplitude from the two inputs.

2.14 MOVEMENT AND NEURO-MUSCULAR BLOCKADE

Rigid fixing of a stimulated limb caused no alteration in CEP or SEP records. However, in three dogs in which pancuronium bromide (dose 0.1 to 0.3 mg kg^{-1}) was used to remove an outbreak of noise in the thoracic electrodes, changes were seen in SEP but not in CEP. When the initial effect wore off, the SEPs returned to their original form and reverted again with a later repeated dose. The change seen in the median-cervical SEP was a reduction of the late slow positive SEP. There were also changes in form of the antidromic SEPs.

2.15 EFFECT OF TIME

A remaining question involved the stability of the preparation with regard to time. Six dogs were prepared for the full range of EP

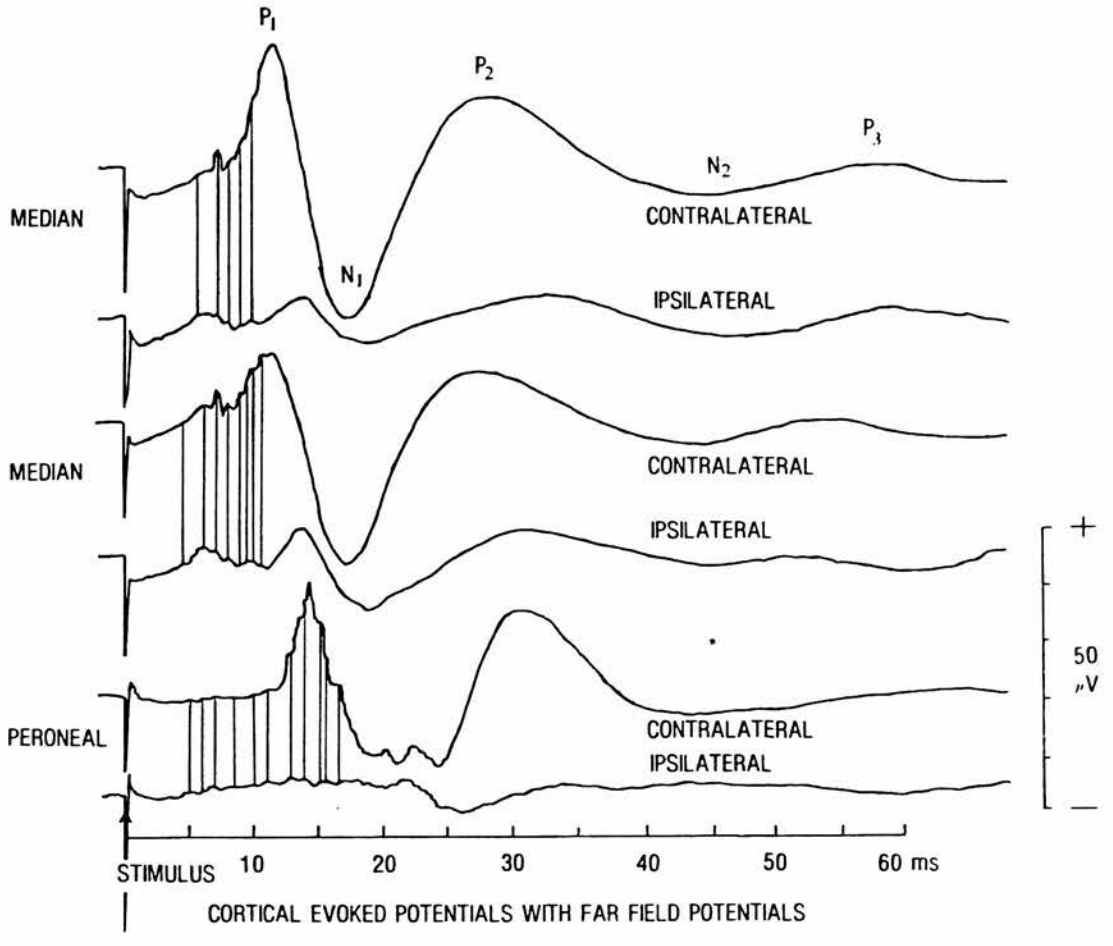


Figure 6. Cortical evoked potentials with far field potentials. Simultaneous ipsilateral and contralateral records from the same stimulus are shown. The far field potentials of the same latency are indicated in typical CEP records.

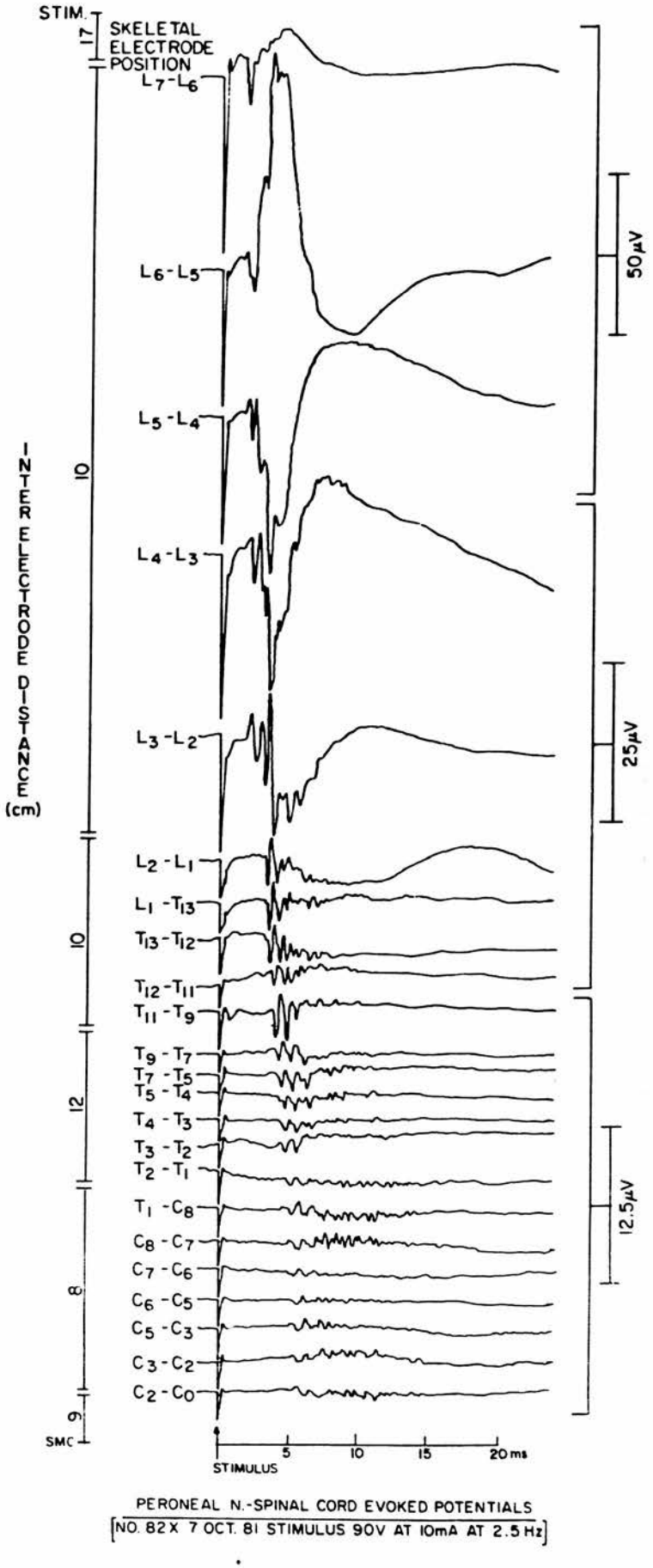


Figure 7. Peroneal nerve-spinal cord evoked potentials. Sequential bipolar SEPs are shown from unilateral peroneal nerve stimulation at the neck of the fibula. Observe the large negative and late, slow positive waves that dominate the root entry zones. Latency and spread increase with distance from the stimulus, while amplitude decreases. The classical root entry zone recordings are inverted caudal to the root entry.

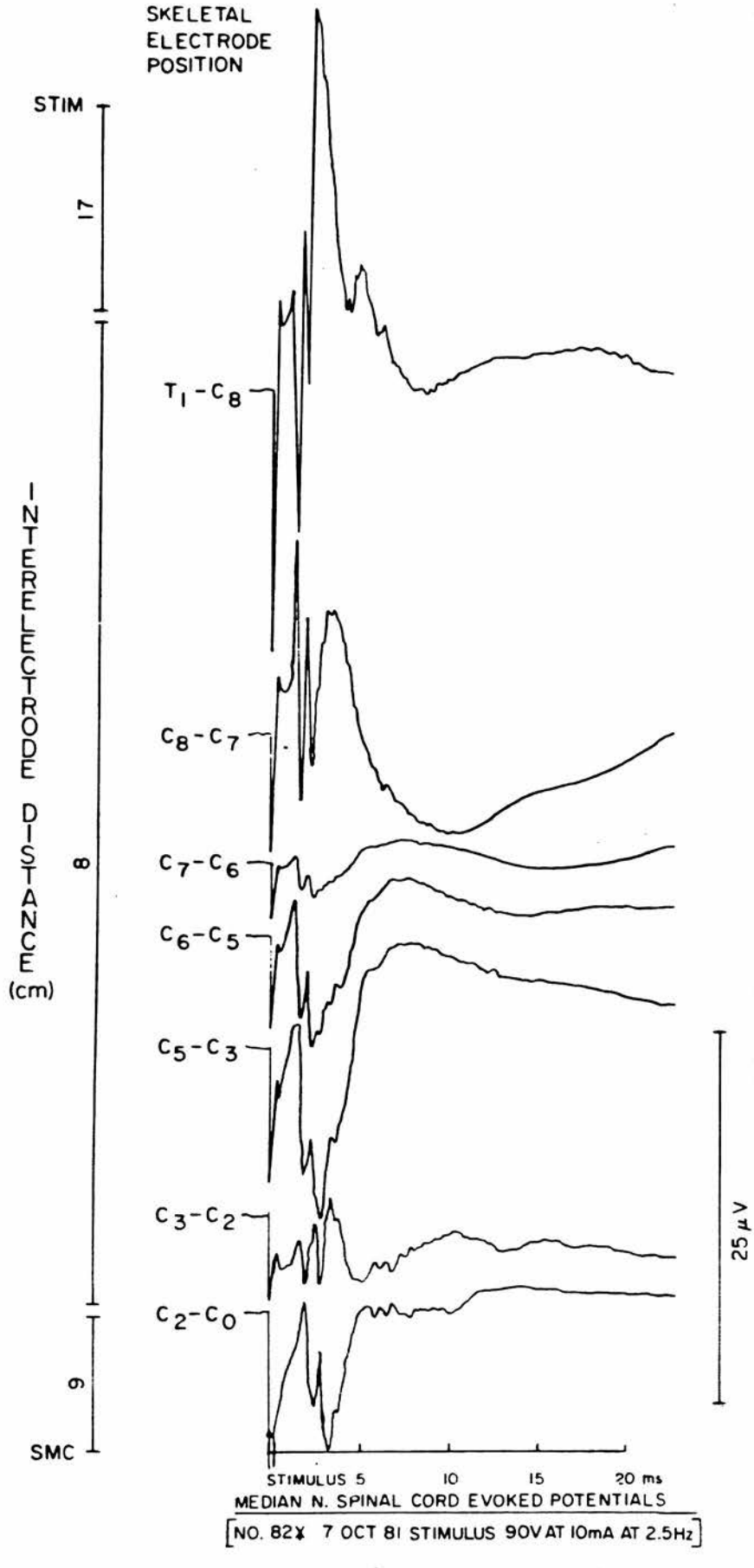


Figure 8. Median nerve -spinal cord evoked potentials. Sequential bipolar SEPS are shown for unilateral median nerve stimulation at the distal end of the humerus. The SEPs show classical cord dorsum recordings for a root entry-zone evoked potential.

recording. Recording was carried out over 5 hr. No change in latency was seen. The amplitude results are given in Table 6. The overall trend was one of a progressive fall in mean amplitude of between 1 and 2% hr^{-1} and an increase in variance with time.

TABLE 6

EFFECT OF TIME ON EVOKED POTENTIALS

(Expressed as a percentage of control)
(N = 6 2-6 measurements per dog per period)

TIME PERIOD (hr)			0-1	1-2	2-3	3-4	4-5	Overall	Range of Amplitude μv (MIN) (MAX)
Peroneal CEP	P_1N_1	$\bar{x}$	100.0	93.2	91.9	92.7	90.1	93.6	7
		SE	5.9	5.2	5.7	6.3	8.7	6.9	108
Peroneal CEP	N_1P_2	$\bar{x}$	100.0	97.6	91.9	88.3	92.8	94.5	7
		SE	5.4	5.8	9.6	6.5	7.9	7.4	97
Lumbar SEP	P_1N_1	$\bar{x}$	100.0	97.8	95.9	91.9	90.2	95.2	5
		SE	2.1	3.7	5.4	5.0	5.6	5.0	101
Median CEP	P_1N_1	$\bar{x}$	100.0	101.6	99.6	97.0	97.4	99.1	4
		SE	2.7	5.3	6.3	6.9	8.6	6.0	74
Median CEP	N_1P_2	$\bar{x}$	100.0	98.5	100.2	96.9	96.0	98.3	1
		SE	4.1	5.7	6.0	7.7	7.2	6.3	38
Cervical SEP	P_1N_1	$\bar{x}$	100.0	97.0	94.2	92.5	94.6	95.7	3
		SE	1.4	2.7	2.6	3.0	3.1	2.9	53
Cervical SEP	Late P	$\bar{x}$	100.0	95.8	95.2	94.5	91.9	95.5	3
		SE	2.2	3.9	4.3	5.8	5.4	4.5	113

2.16 TEMPERATURE

In two dogs, temperature was altered above and below the normal mean of 38°C by 2°C without apparent effect upon evoked potentials.

SECTION 3

THE EFFECTS OF GAS PRESSURE ON EVOKED POTENTIALS

THE EFFECTS OF GAS PRESSURE ON EVOKED POTENTIALS

3.1 PREAMBLE

Visual and auditory evoked responses (VER, AER) have been widely used as measures of inert gas narcosis (Fowler and Ackles, 1977). Somatosensory cortical evoked potentials have been applied in this condition less commonly (Langley, 1976; Langley and Hamilton, 1975). Whether or not evoked potentials provide a true measure of narcosis continues to be debated because they do not necessarily correlate well with independent measures of cortical performance (Fowler and Ackles, 1977). The effect of narcosis is thought to be one of interference with synaptic transmission primarily in the brain (Bartus and Kinney, 1975, Bennett, 1966). It is interesting, however, that although in any given group the overall effect on evoked responses is one of depression, the range of effect can often be very wide, even showing a slight increase above baseline values at pressures of up to 11 bar in some individuals (Bartus and Kinney, 1975). The narcotic effect has also been attributed to oxygen as well as to nitrogen (Bennett et al., 1969; Hesser, 1963).

As the objective of this project was to study the treatment of DCS at pressure and there was a parallel study into the treatment of arterial gas embolism, it was considered to be essential to know the full range of possible effects of the expected hyperbaric conditions upon the variables to be measured. Most of the observations reported were made during the preparatory phases of DCS experiments but a small number were made during specifically dedicated experiments.

The questions asked were:

a) How much of a depressing effect did various pressures of air have on measurements made at pressure?
b) Is there an equilibration time for the expected changes in EPs following a step change in pressure?
c) Does hyperbaric oxygen have any effect upon EPs?
d) Does prolonged exposure to high pressure air or oxygen have any progressive effect?
e) For comparative purposes how do 20% oxygen-helium mixed affect EPs over the same pressure range as air?

f) Are SEPs and CEPs equally affected or are any components more affected than others?

3.2 METHOD

The results from 61 dogs weighing between 9 and 21 kg were used in this study. The dogs were prepared in the standard fashion, previously described. The primary measurements were peak-to-peak amplitudes of P_1N_1 and N_1P_2 in the CEPs, and of P_1N_1 in the SEPs. The last 16 studies were also assessed using the peak-to-peak summation method adopted in the final experiments.

When the animal was placed in the compression chamber, and was stable within the desired range of physiological measurements, between four and six sets of control evoked potentials were obtained for each stimulus site. The chamber was then closed and with the appropriate breathing gas on line to the ventilator, compression with air at a rate of 75 ft. min^{-1} was begun. The ventilator exhaust was connected to a 100 litre Douglas bag. This was vented outside the chamber to remove oxygen and so reduce the fire hazard. Modifications to the ventilator allowed control of cycle rate and inspiratory flow rate from outside the chamber so that $F_{ET}CO_2$ was maintained at 3.5 - 4.5% surface equivalent as measured by a Beckman LB2 CO_2 analyser. The animals were subjected to the dive profiles shown in Table 7.

About 2 minutes after each pressure change, EP recording was begun. All records weremade in pairs. Results are expressed as a percent of mean control EP amplitude values for each dog. One way analysis of variance was performed where a significant difference between groups was sought.

3.3 RESULTS

Examples of actual recordings taken from one dog are shown in Figure 9 where the effect of breathing air at 300 ft (10 bar) may be seen. All animals were maintained within the normal range for rectal temperature, acid-base state and blood gases.

The results from each profile were first studied separately.

TABLE 7

DIVE DESCRIPTIONS FOR NARCOSIS STUDY

PROFILE	N	DIVE PROFILE (fsw (GAS) x min.)
1	11	60 (O_2)x10; 165(A)x10; 230(A)x45
2	7	230(A)x45
3	17	300(A)x15
4	3	60(O_2)x10; 165(A)x10; 60(O_2)x10; 0(A)x40; 165(A)x10; 60(O_2)x120
5	3	60(A)x10; 60(O_2)x120; 165(A)x10; 0(A)x40; 60(A)x10; 165(A)x10; 60(O_2)x10.
6	3	60(A)x10; 165(A)x 120; 60(A)x10.
7	9	60(O_2)x20; 165(A)x 20; 60(O_2)x20.
8	8	165(A)x20; 60(O_2)x20.
9	3	230(He)x10; 300(He)x10; 165(He)x10; 60(He)x10; 60(O_2)x10.
10	2	60(He)x10; 165(He)x10; 230(He)x10; 300(He)x10.
11	6	0(A)x300

All profiles preceded by 60-100 min. control period. Profile 10 followed profile 5, and profile 6 followed profile 9 in the same dogs with a 60 min surface interval. Times are approximate. Breathing gases were (O_2) - 100%; (A) - air; (He) - 20% O_2/80% He. Total N = 61. In profiles 7 and 8 only Median CEP was recorded.

This revealed that regardless of profile, the effect of any given condition with the same breathing gas, was the same. Therefore, the results from all profiles using the same gas were pooled. At no time was any effect on latency seen which could be attributed to gas, pressure or time. The data used in the air and oxygen study were drawn from the first 20 minutes of any given exposure.

While breathing oxygen at 60 ft (2.8 bar) there was a marginal but insignificant depression of P_1N_1 in peroneal and median CEP, which tended to be restored on returning to air breathing at the surface.

The effects of the various pressures on CEP and SEP in air breathing dogs are shown in Table 8 and Figures 10 and 11. There was a significant depression of both P_1N_1 and N_1P_2 in CEPs proportional to pressure up to 230 ft (8 bar). It appeared that by 300 ft (10 bar) after a linear response to pressure, there was at least a levelling off of the effect if not an actual reversal. When breathing 20% oxyhelium instead of air no effect of pressure was seen (Table 9). In those profiles (4, 5, 7 and 8 in Table 7) where dogs were returned to surface free from risk of decompression sickness CEPs returned towards control values upon surfacing.

No significant depression of P_1N_1 was seen in the SEPs. The SEPs measured in air and oxyhelium were almost the same (Table 8, Figure 11, and Table 9). However, the amplitude of the cervical SEP late P wave was significantly reduced while breathing air, although to a lesser extent than were the CEP's (Table 8, and Figure 11).

The effects of continuous exposure to pressure for up to 2 h are shown in Table 10. Neither with continuous oxygen at 60 ft (2.8 bar) nor air at 165 ft (8 bar) was there any evidence of an accelerated deterioration beyond that due to time alone as seen at atmospheric pressure. The actual changes seen were comparable with acute changes shown in the pooled data presented in Table 8. On return from 2 h of oxygen breathing at 60 ft (2.8 bar) to air breathing at atmospheric pressure, there was no change in CEP amplitude so that the final level was comparable with what time alone might produce (Table 6).

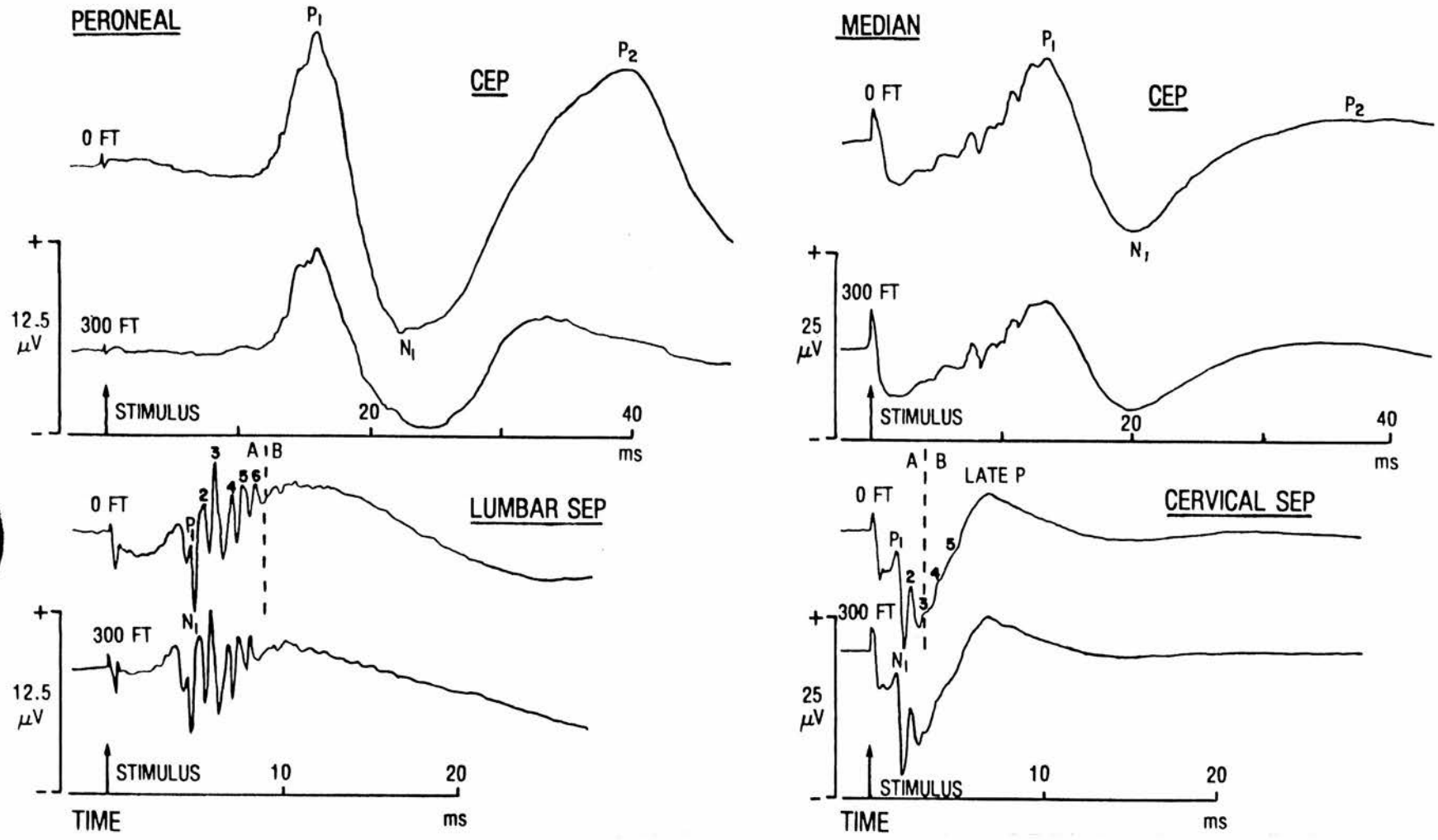


Figure 9. The effects of narcosis on peroneal and median CEPs and SEPs in one dog. Stimulation at 100 V, 10 mA at 2.5 Hz (n = 128). The first record of each pair was the control record and the second was at 300 ft (10 bar).

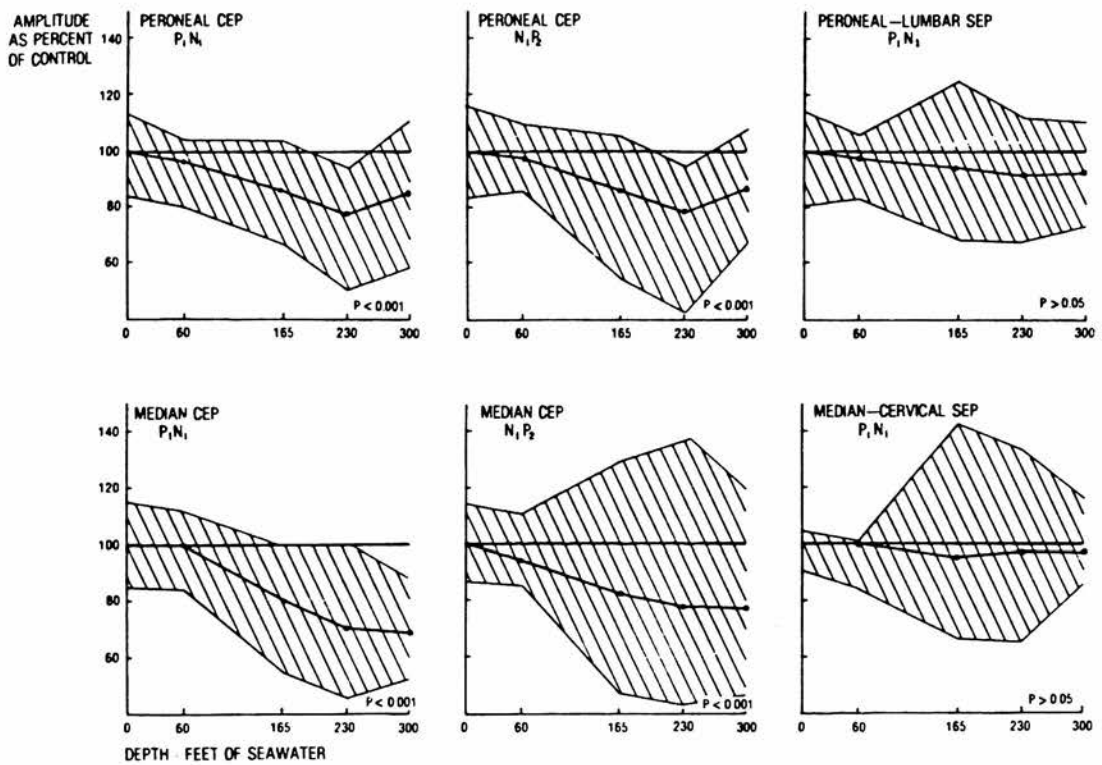


Figure 10. Effect of air pressure on peroneal and median CEPs and SEPs. The shaded area represents the range of results. The level of significance of the difference between groups by ANOVAR is given on each graph.

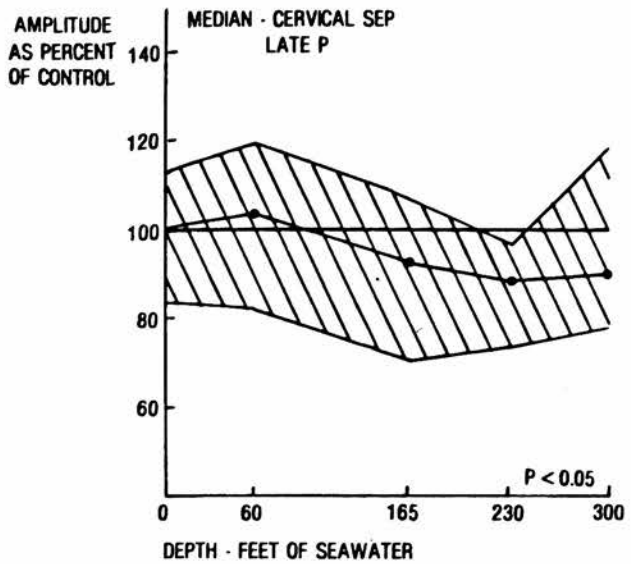


Figure 11. Effect of air pressure on late positive wave of median-cervical SEP. The shaded area indicates the range of results.

TABLE 8

EFFECT OF PRESSURE ON EVOKED POTENTIALS WHILE BREATHING AIR OR OXYGEN.

Depth (fsw)		Surface	60(O_2)	60(A)	165	230	300
Peroneal P_1N_1 CEP	$\bar{x}$	100.0	94.6	95.8	85.6	77.6	85.4
	SE	1.2	2.9	1.4	2.1	3.7	3.2
	n	46	17	5	23	18	17
Peroneal N_1P_2 CEP	$\bar{x}$	100.0	98.2	97.3	86.4	78.3	87.1
	SE	2.1	2.7	2.4	2.4	3.9	2.8
	n	46	17	5	23	18	17
Lumbar P_1N_1 SEP	$\bar{x}$	100.0	99.1	97.6	94.3	91.7	92.6
	SE	1.1	3.2	3.3	2.3	2.7	2.4
	n	45	17	5	23	17	17
Median P_1N_1 CEP	$\bar{x}$	100.0	95.0	99.5	80.8	70.5	68.8
	SE	1.2	2.3	3.4	2.4	2.8	3.3
	n	39	17	5	23	16	12
Median N_1P_2 CEP	$\bar{x}$	100.0	96.9	94.7	82.9	77.8	77.2
	SE	2.3	2.8	4.9	3.3	3.9	6.9
	n	39	17	5	23	16	12
Cervical P_1N_1 SEP	$\bar{x}$	100.0	96.8	100.0	95.6	97.8	97.0
	SE	0.7	1.9	0.6	3.0	3.6	2.3
	n	40	17	5	23	17	12
Cervical Late P SEP	$\bar{x}$	100.0	97.4	103.2	92.4	88.3	90.0
	SE	1.2	1.7	4.4	1.6	1.7	3.6
	n	40	17	5	23	17	12

Percent of mean surface control ± SEM. The pooled results from dive profile 1-6 but excluding the last 80 min of the 120 min studies at 60 ft (O_2) and 165 ft (A). Control data has $\nmid$ 5 replicates per dog and all other entries $\nmid$ 2 replicates.

An attempt was made to detect an effect of inert gas wash-in from the data given in Table 11. Routinely after every step change in pressure, two peroneal CEPs were recorded followed by two median CEPs. If the exposure was longer than 15 min the cycle was repeated. Table 11 contains the results from all three gases at all pressures tested. Firstly, the direction of change between the first and second recordings (peroneal) and third and fourth recordings (median) was tested by chi-square. There were significantly more reductions from first to second recordings than from third to fourth recordings ($P < 0.01$). This effect was apparent over approximately the first 6 min after a step change of pressure while

breathing air. It was not apparent when breathing oxygen or oxy-helium.

There appeared to be a further reduction between the second and third recordings although its significance was not tested because this would have entailed crossing between peroneal and median recordings. This suggests an asymptote for narcotic effect at about 10 min.

TABLE 9

EFFECT OF PRESSURE ON EVOKED POTENTIALS WHILE BREATHING 20% OXYGEN IN HELIUM

	Depth (fsw)		Surface	60	165	230	300
Peroneal CEP	P_1N_1	$\bar{x}$	100.0	104.6	101.8	98.5	96.7
		SE	3.0	6.1	5.1	5.0	3.8
Peroneal CEP	N_1P_2	$\bar{x}$	100.0	104.0	102.7	101.3	97.5
		SE	3.0	3.4	5.3	5.9	3.9
Lumbar SEP	P_1N_1	$\bar{x}$	100.0	95.7	94.6	96.0	95.0
		SE	1.4	1.3	2.6	1.5	1.6
Median CEP	P_1N_1	$\bar{x}$	100.0	96.3	95.7	93.4	98.0
		SE	2.1	3.5	4.3	3.5	5.0
Median CEP	N_1P_2	$\bar{x}$	100.0	98.5	98.7	98.6	99.1
		SE	2.9	4.1	7.2	4.3	4.8
Cervical SEP	P_1N_1	$\bar{x}$	100.0	97.2	96.3	98.1	96.0
		SE	0.3	2.2	2.3	1.8	1.9
Cervical Late P SEP		$\bar{x}$	100.0	97.2	96.3	98.1	96.0
		SE	0.3	2.2	2.3	1.8	1.8

Percent of mean surface control ± SEM N = 5. Control data has four replicates per dog and other entries, two replicates.

In the 230 ft (8 bar) air breathing group, which followed the trend already outlined, it is noteworthy that the next pair of peroneal recordings (No. 5 and 6) were the same (70.8%) as the preceding median recordings (70.5%) and also the final pair of medians (No. 7 and 8) (69.6%), indicating a plateau.

TABLE 10

THE EFFECT OF TWO HOURS EXPOSURE TO 2.8 BAR OF OXYGEN AND & BAR OF AIR ON EVOKED POTENTIALS

			60 fsw - oxygen (N = 6)			165 fsw - air (N = 3)		
Time period (Min)			0-40	41 -80	81-120	0-40	41-80	81-120
Peroneal CEP	P_1N_1	$\bar{x}$	100.6	105.1	106.5	86.7	85.8	83.7
		SD	9.6	18.3	21.0	2.1	2.1	3.6
Lumbar SEP	P_1N_1	$\bar{x}$	93.5	91.9	94.3	92.8	94.7	91.4
		SD	23.4	29.9	28.0	7.8	7.0	5.0
Median CEP	P_1N_1	$\bar{x}$	96.7	92.5	95.7	89.2	88.0	86.6
		SD	12.9	13.7	21.4	4.0	4.5	3.2
Cervical SEP	P_1N_1	$\bar{x}$	96.8	98.9	101.5	94.7	91.6	88.9
		SD	3.6	5.9	6.3	2.9	5.3	7.1
Cervical Late P SEP		$\bar{x}$	98.3	96.7	95.5	93.3	94.6	94.8
		SD	8.0	7.8	6.6	4.0	6.4	6.6

Results expressed as a percent of surface control values ± SD.

In a group in which only median CEPs were measured the same observations were made. There was no consistent change seen with oxygen at 60 ft (2.8 bar). Mean values for four consecutive measurements (n = 17) were 96.8 ± 4.1, 96.2 ± 4.6, 89.9 ± 4.6, and 94.7 ± 5.6. With air breathing at 165 ft (6 bar) there was again a significant difference for the direction of change by chi-square ($P < 0.001$) between the first and second pairs of recordings. This was also evident by paired "t" test ($P < 0.01$). The mean values for the four consecutive measurements (n = 17) were 86.5 ± 3.4, 79.5 ± 3.4, 77.3 ± 4.6, and 78.1 ± 4.5. Evidence for wash-out was sought in the dogs which went from 165 ft (6 bar) on air to 60 ft (2.8 bar) on oxygen (profiles 4, 5, 7 and 8 in Table 7). There was an insignificant increase in the group means between first and second recordings of from 1 to 3% following arrival at 60 ft (2.8 bar).

TABLE 11

EFFECT OF INERT GAS WASH-IN ON CORTICAL EVOKED POTENTIAL AMPLITUDE.

Gas		Air				O_2/He				O_2
Depth	(fsw)	60	165	230	300	60	165	230	300	60
Peroneal	1	96.0	87.1	80.1	88.3	101.3	97.1	92.0	92.6	94.0
		1.9	2.3	5.1	4.0	4.8	4.6	3.5	2.7	2.2
	2	95.5	84.2	74.0	85.1	96.6	96.3	94.7	91.1	94.7
		2.2	2.2	3.0	4.9	6.8	5.2	3.9	4.3	2.3
	Δ	-0.5	-2.3	-5.9	-3.2	-4.7	-0.8	+2.7	-1.5	+0.7
Median	3	96.3	82.1	70.6	67.7	96.3	97.3	92.0	88.1	97.2
		3.3	2.6	3.1	3.5	4.3	4.2	5.0	3.9	2.2
	4	96.7	81.2	70.1	69.9	96.8	94.4	91.0	90.1	95.8
		3.1	2.6	3.2	3.3	4.0	5.0	4.8	5.3	2.6
	Δ	+0.4	-0.9	-0.5	+2.2	+0.5	-2.9	-1.0	+2.0	-1.4

Results expressed as percent of mean control value ± SEM. The first pair of CEPs (Peroneal) were recorded between 1 and 6 min after arrival at the stated pressure. The second pair of CEPs (Median) were recorded between 6 and 12 min after arrival at the stated pressure. The mean values at 230 ft (Air) for a second pair of peroneal CEPs taken at 20 - 30 min were 70.7 ± 3.29 and 71.0 ± 3.50.

In assessing SEP, the study began by using the first of the travelling waves, P_1N_1. Later a summation of amplitude was used. P_1N_1 and the summed amplitude (Σ amp) were compared in 48 sets of SEP measurements from the 16 dogs entered into the new system. A linear correlation was performed on the data plotting Σ amp against P_1N_1. This produced the relationship Σ amp = 22.12 ± 0.733 (P_1N_1) with $r^2 = 0.6686$. At about 79% the Σ amp and P_1N_1 regression lines crossed. The two variables were not significantly different by paired "t" test ($t = 2.00$ with 47 df).

3.4 DISCUSSION

Two facts emerge from the literature regarding evoked potential measurement at pressure. One is that experimental numbers are commonly very small and the other is that reported results are widely divergent even within the same experimental group. Only one group has reported

the use of somatosensory cortical evoked potentials in studies of the effects of nitrogen. They reported the effects to be similar to those on other EPs (Langley, 1976; Langley and Hamilton, 1975). All other groups have relied on auditory or visual evoked potentials. Another variable involves the subjects, which have included man, awake animals and anaesthetised animals. Breathing gases from masks in contrast to ventilation through an endotracheal tube, is also a potential source of variability. The surrounding gas can leak through poor seals; a problem well recognised in older mask designs. Masks are also prone to cause some CO_2 build-up because of the increased dead space, a factor known to exacerbate narcosis (Bennett, 1976). Clearly, breathing chamber atmosphere or gas supplied through a cuffed endotracheal tube are the only reliable ways of supplying a precisely known breathing gas. Any circumstances where an animal breathes one gas while surrounded by another will result in some cutaneous transfer, although the effect will undoubtedly be trivial.

In both the median and peroneal CEP results, an approach to an asymptote is suggested between 230 and 300 ft while air breathing. Bennett et al. (1969) saw a similar effect but regarded it as experimental variation. Kinney et al. (1977) refer to an asymptote for nitrogen in the region of 300 to 400 ft. There are no clear reasons why this should occur. The possibility of a saturation of the effect of nitrogen seems unlikely at this pressure as behavioural changes continue to increase at greater pressures. If it were not that oxygen is also alleged to be narcotic and should therefore have a synergistic effect (Bennett et al., 1969; Hesser, 1963), the possibility of a stimulating effect from the oxygen with a partial pressure approaching 2 bar might be considered as having some reversal effect on the EP suppression by nitrogen. However, the short time scale excludes a mechanism associated with classical acute cerebral oxygen toxicity.

The range of individual responses seen in these data was similar to that reported by Bartus et al. (1975) where even at a pressure of about 11 bar some records were greater than controls. The degree of mean suppression of groups was also widely variable. Air breathing at 200 to 300 ft has produced EP suppressions ranging from levels similar

to these (Ackles and Fowler, 1971) to twice as great as these (Bennett et al., 1969; Schatte and Bennett, 1973). It can be confirmed that the effect of air at pressure on somatosensory CEP is similar to that on auditory and visual CEP. The only report of a latency shift by Kinney et al (1974) is at odds with these findings and those of Ackles and Fowler, (1971), Bennett et al. (1969), and Hesser (1963).

The reported work on EPs while breathing oxyhelium in the pressure range of interest here has largely been done with awake men and animals (Bennett et al., 1969; Schatte and Bennett, 1973). They report a depression of about 30% in AER at 300 ft and about 20% at 200 ft where no apparent change was seen here. It may be that the anaesthesia in these animals has already caused that amount of suppression. Certainly if one deducts 30% from those results and also the air results reported by the same authors then the findings are the same. This might suggest a synergistic effect of narcosis with pentobarbital. It may also be that the many extraneous effects of compression of which the conscious man/animal is aware could also have an adverse influence upon EP measurement.

Bennett (1963) reported a reduction in cat spinal reflex activity during air breathing at pressures of 7 to 9 bar. He likened the effect to the asphyxia effects on the segmental SEPs recorded from the cord dorsum described by Gelfan and Tarlov, (1955). Looking at the initial travelling wave as opposed to the static wave of the root entry in the SEPs and also the summed amplitude of the principal early waves, showed a slight downward trend in amplitude which was not significant. However, the late slow P wave in the median - cervical SEP showed a significant change inversely related to air pressure. The depression was considerably less than that seen in the CEP at the same pressures. this wave may be related to interneuronal activity and possibly to local reflexes (Gelfan and Tarlov, 1955). These findings would therefore tend to corroborate those of Bennett(1963). The relationship between the three types of EPs; SEP long tract travelling waves (mostly non-synaptic), SEP late P waves (interneuronal local events), and CEP (multiple synaptic transmission) and the relative effects of narcosis, lend support to the idea that the inert gas effect is the result of

interference with synaptic transmission (Bennett, 1966). The effect is evidently mostly in the brain as suggested by Bartus and Kinney (1975) where the density of synapses is greater.

The literature appears to contain no references to the ability to detect the effect of inert gas wash-in upon the EPs. The appearance of a plateau by about 8 to 10 min is compatible with opinion regarding the time for inert gas exchange in the brain (Jones, 1951; Weathersby et al., 1981). With much smaller pressure changes in the decompression phase a similar but insignificant reverse trend was observed.

After reaching equilibrium following a step pressure change, there was no indication that the additional pressure caused an acceleration of the small deterioration expected as a result of time alone.

Although Bennett et al. (1969) and Hesser (1963) have stated that oxygen has a narcotic effect comparable with that of nitrogen this was not confirmed. A slight reversible effect was seen in the 10 min exposures, but was not seen in the 20 and 120 min exposures. Ray and Hawgood (1977) also failed to find the effect, although the late effects of acute toxicity caused a progressive loss of EP amplitude after between 60 and 100 min breathing 5.76 bar of oxygen. Their animals like these were anaesthetised. The possibility of the surrounding influences contributing to the effect in alert men or animals must again be considered as an alternative to an effect attributable to the gases breathed. For this reason in the clinical area, efforts are made to remove all extraneous influences when measuring CEPs (Cracco, 1972; Goff et al, 1962). In compression experiments this is well nigh impossible.

The discrepancy between the observations of no significant change in EP while breathing oxygen or oxyhelium at pressure, and the observations of Bennett et al. (1969) that a decrement occurs, although without any observable loss of performance, clearly supports Fowler and Ackles' (1977) doubts concerning EPs as measures of narcosis. This study allowed the calculation of a correction factor for CEPs measured at pressure particularly inother studies. This was not necessary for the SEPs.

SECTION 4

HOW DO SPINAL EVOKED POTENTIALS CHANGE?

4.1 Asphyxia

4.2 Blood Pressure

4.3 Cordotomy

HOW DO SPINAL CORD EVOKED POTENTIALS CHANGE?

4.1 ASPHYXIA

There was no local experience of how SEPs might change with DCS or with the systemic changes that occur with DCS. During the development of the method some guidelines were required to prepare the author for what changes might be seen. At the end of some control studies continuous peroneal SEP recordings were made after death. In others the anaesthesia was maintained after the ventilator was disconnected and the endotracheal tube occluded. Figure 12 shows the sequence of changes in two dogs correlated with mean blood pressure.

The first major point is that latency is not noticeably affected until amplitude is much reduced. Secondly, in a generalised hypoxaemia, the later slower waves are reduced first. Dog No. 916 showed an occasionally observed phenomena when the timing of recording was right. There may be a generalised increase in amplitude before the reduction begins.

4.2 BLOOD PRESSURE

In a separate study into developing a means of monitoring spinal cord function during paediatric spinal cord surgery, which would avoid the need to wake children in mid operation, the effect of lowered blood pressure was studied in several dogs. Some examples of the changes in SEP correlated with mean blood pressure are shown in Figures 13, 14 and 15. There was an infinitely variable response to hypotension with a significant loss of amplitude when mean blood pressure fell into the range below 60 to 30 mm Hg. This being the range below which cord blood flow autoregulation fails (Sandler and Tator, 1976). There was again a tendency for the later travelling waves to lose amplitude first. Dog No. 922 (Fig. 13) in the left median SEP shows the relative sensitivity of the local functions with most of the amplitude loss occurring in the late slow positive wave.

The last SEP in Dog No. 923 (Figure 14) shows how subsidiary waves previously masked by a larger wave can be uncovered as amplitude and latency change.

4.3 CORDOTOMY

A series of partial cordotomies confirmed that most of the SEPs recorded by this method were transmitted through the dorsal columns. However there were contributions from the ventral and lateral columns.

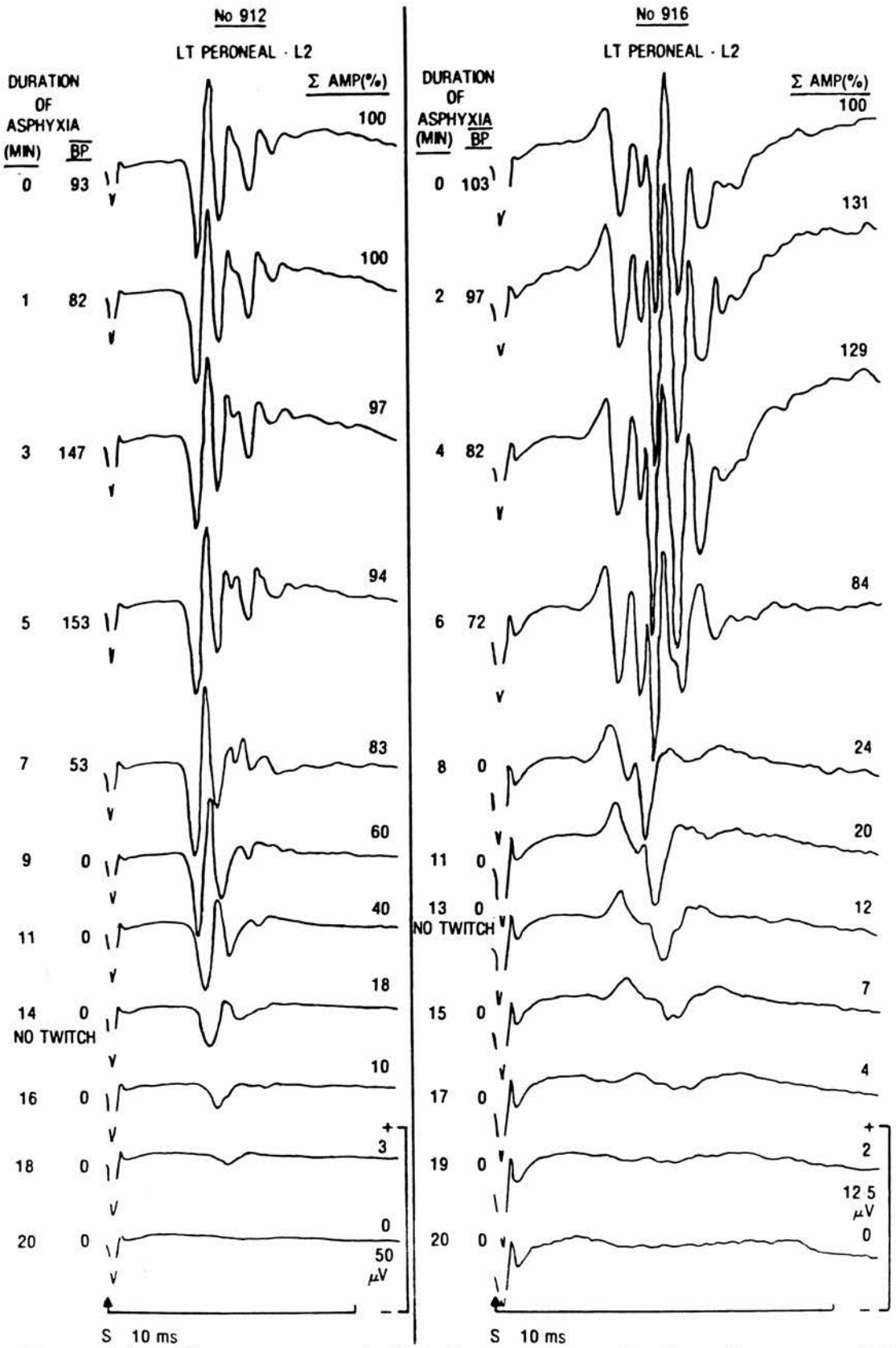


Figure 12. The sequence of SEP changes in asphyxia. Mean arterial blood pressure and summated SEP amplitude as a percentage of control are shown.

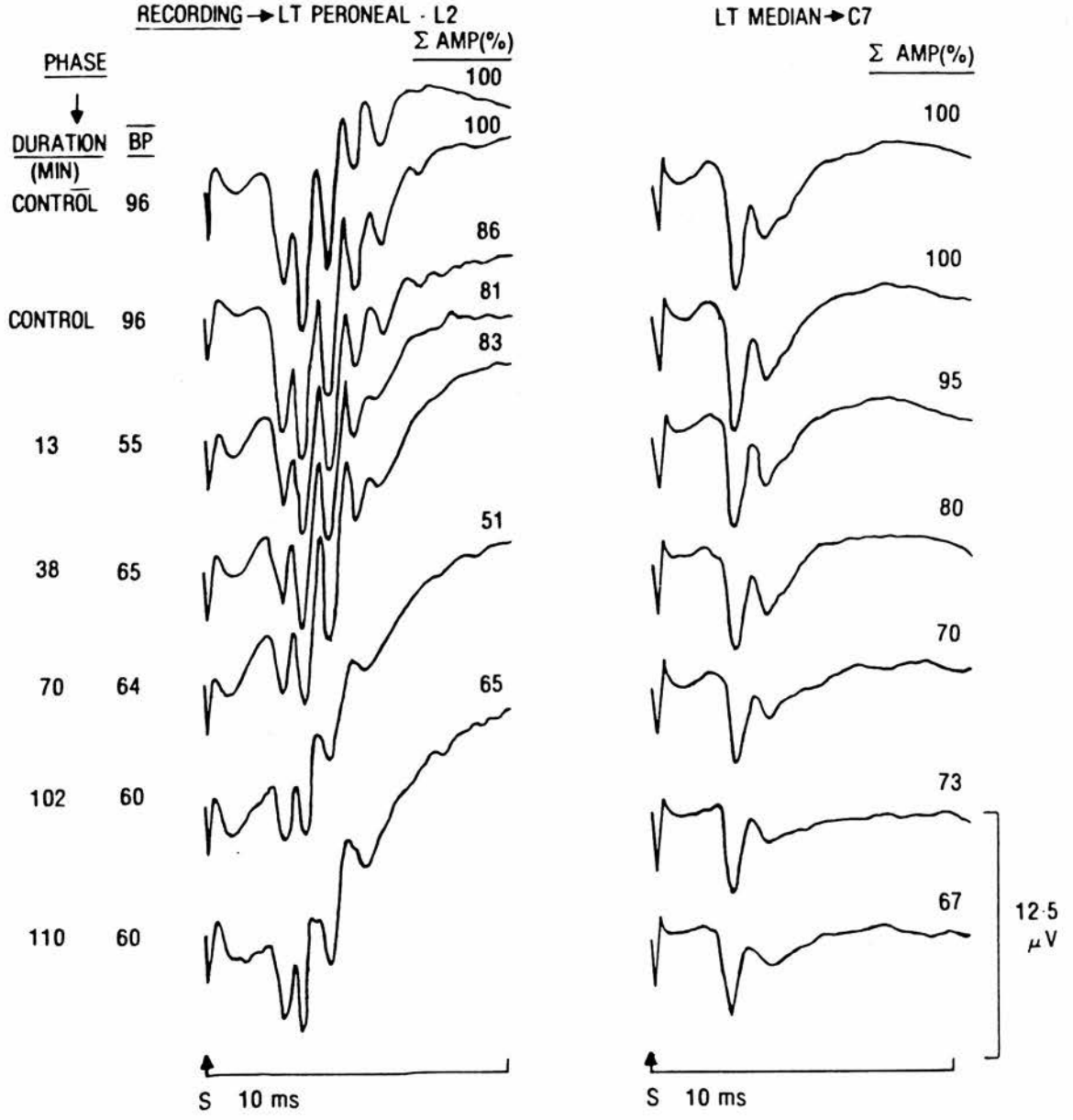


Fig. 13. Changes in SEPs related to blood pressure. Dog. No. 922. Mean blood pressure, experiment time and summated amplitude are shown for peroneal and median SEPs.

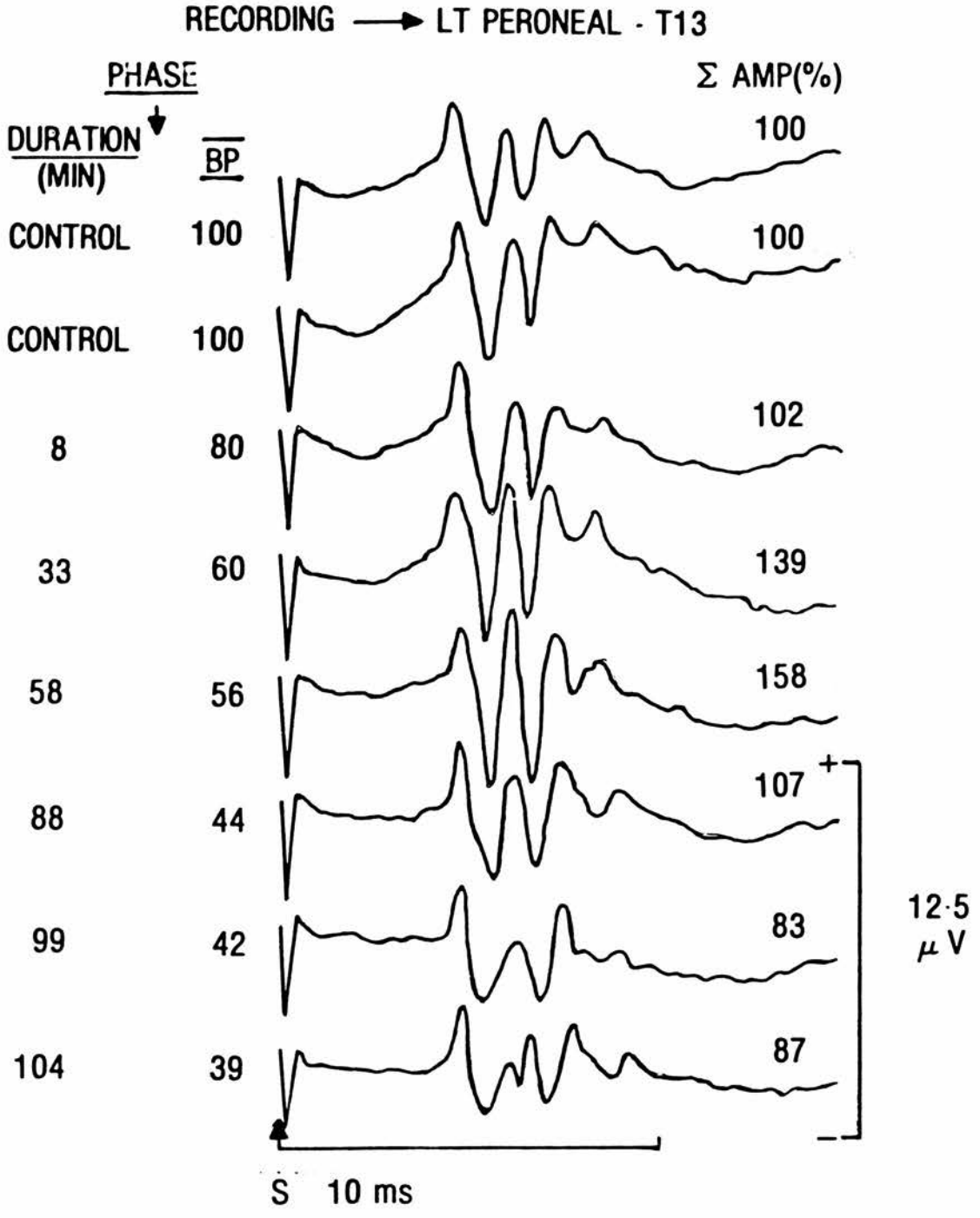


Figure 14. Changes in SEPs related to blood pressure. Dog. No. 923.

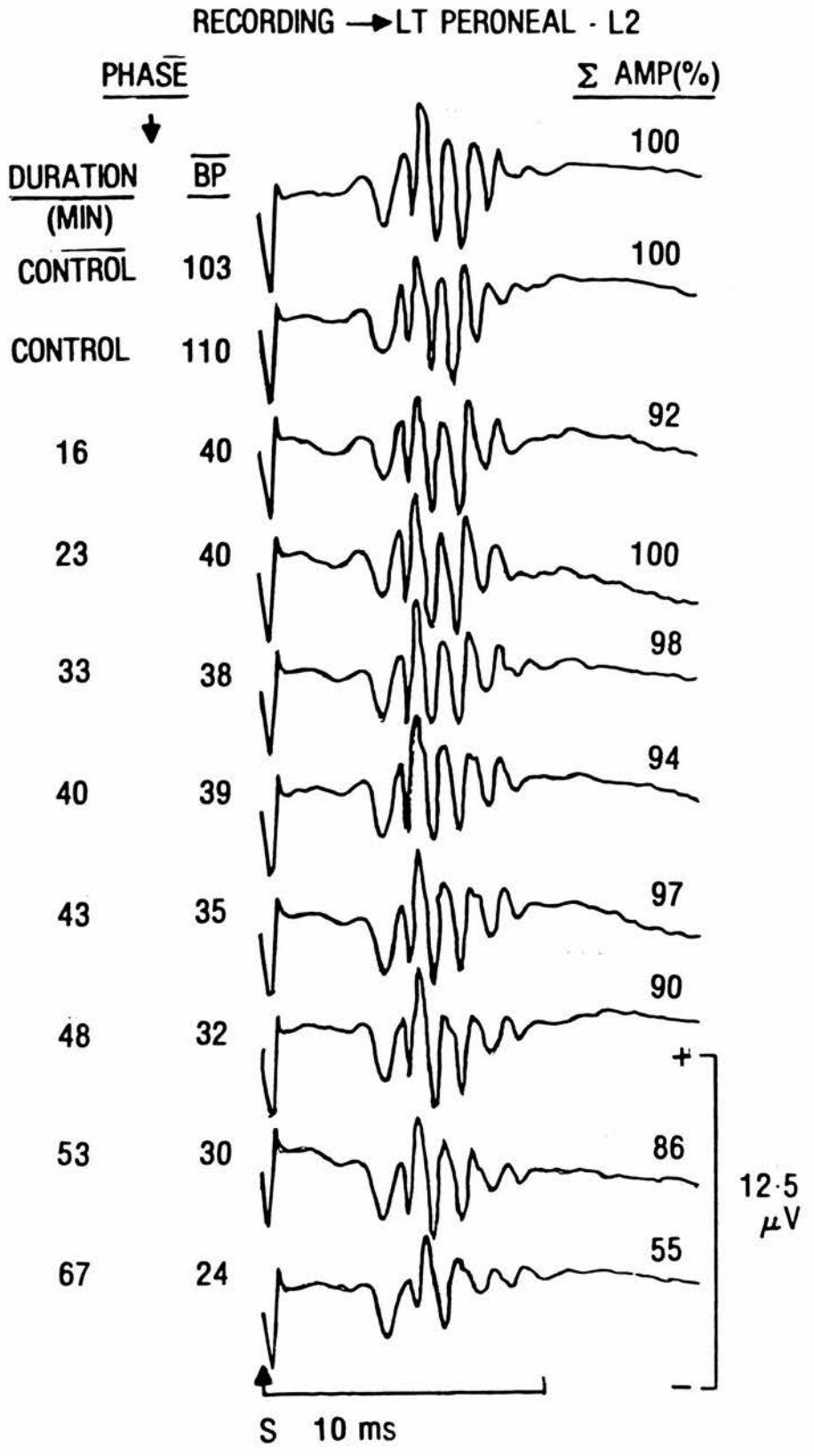


Figure 15. Changes in SEPs related to blood pressure. Dog No. 925.

SECTION 5

THE DEVELOPMENT OF THE PHYSIOLOGICAL MODEL AND THE DIVE

5.1 Preamble

5.2 Method

5.3 Results

5.4 Discussion

THE DEVELOPMENT OF THE ELECTROPHYSIOLOGICAL MODEL AND THE DIVE

5.1 PREAMBLE

The objective of this phase was to develop a reliable means of remotely monitoring anaesthetised dogs for signs of spinal cord DCS. The means of monitoring had to be quantifiable to enable statistical analysis to be made of the severity of, and recovery from DCS. The ability to at least roughly localise the sites of lesions was also sought.

Decompression sickness is a notoriously unpredictable and difficult disease to develop and control. This meant that any dive used to produce the desired spinal cord lesions would have a fairly high attrition rate. As the objective was to study delayed treatment a further complication was added to the model.

There were several dog models of DCS, some of which were known to produce spinal cord problems (Behnke and Shaw, 1937; McIver and Leverett, 1964; Wells et al., 1971). A modified version of that described by Bove et al. (1974) was selected for use.

There were, however, certain constraints which had to be imposed on the model. The model had to be capable of surviving without chemotherapy on the surface for long enough to allow the cord lesion, once diagnosed, to consolidate and thus assume the characteristics of the delayed treatment case. Furthermore, as perfusion pressure in the neuraxis could reasonably be assumed to be relevant in treatment, severe hypotension had to be avoided. It is well recognised that fluid loss from the vascular space can be a major problem (Arturson and Grotte, 1971; Bove et al., 1974; Cockett et al., 1965), and liberal fluid administration is generally recommended in decompression sickness treatment (Davis, 1979). Therefore, hypotension and haemoconcentration could reasonably be corrected by infusion of Ringers Lactate. This and correction of acidosis were the only additional therapies permitted.

5.2 METHOD

Dogs weighing between 6 and 22 kg were prepared in the prescribed fashion as required. Full control data were acquired before the start of the dive.

All initial dives were carried out breathing air with a compression rate of 75 ft min^{-1}. Bottom times refer to time spent at maximum pressure. Decompression was at 60 ft min^{-1} to 60 ft and slower from there to the surface. If a first dive failed to produce DCS within 30 - 40 min, animals were redived but for a shorter period. The Bove et al. (1974) model required a "controlling recompression" after the first signs of cardiopulmonary involvement to prevent complete cardiovascular collapse. This return to 70 ft stabilized the condition and was followed by a long decompression to prevent recurrence of cardiopulmonary collapse.

The development is reported in four parts. The early dives were to 230 ft (8 bar) and initially only CEPs were monitored. Once measurement of SEPs became reliable, the 230 ft dive and subsequent manipulations were modified in an effort to produce a treatable model of decompression sickness. The second phase ended with similar dives to 230 ft but without having produced a physiologically stable animal model of cord DCS. The third phase will only be mentioned in the discussion and entailed searching for a way to produce cord DCS in an only moderately sick animal. The final phase covered the exploration of a short dive to 300 ft (10 bar) which produced the required model of cord DCS.

Initially the dives and acquisition of EPs were developed in parallel. The first major change in design resulted from the observation of a high incidence of cerebral DCS as indicated by a loss of EEG amplitude. This unexpected event removed the ability to monitor cord function via the cortex, and forced the development of a technique for directly measuring cord function using SEPs. Cortical evoked potentials continued to be measured because the far field potentials provided some indications of upper cord and brain stem involvement.

5.3 RESULTS

The initial phase began with dives as long as 61 min at 230 ft (8 bar). Dives were shortened by amounts related to three groups of body weight. The following bottom times produced DCS: < 10.0 kg, 50 - 61 min; 10.0 - 13.0 kg, 39 - 59 min; > 13.0 kg, 37 - 60 min. In the larger group of 10.0 - 13.0 kg weight, there was a tendency for onset time to be inversely related to bottom time. For dives of 51 min. and longer, mean onset time was 3.0 min (n = 4) and for shorter dives mean onset time was 7.3 min (n = 7). In this first group of 17 dogs the onset of DCS took various forms, some of which occurred simultaneously (form of DCS - No. of dogs): elevation of RVP and CSFP - 7; loss of EEG amplitude - 9; elevation of CSFP and depression of EEG - 3; loss of EEG only - 3; elevation of CSFP only - 2; loss of CEP only - 1; hypotension (systolic AoP < 100 mm Hg) - 2; hypertension - 1. Loss of EEG amplitude invariably reduced CEP. These dives resulted in 15 controlling dives to stabilise the animal. Decompression from 70 ft lasting 18 to 41 min only reached the surface occasionally and the majority were held at pressures between 10 and 30 ft to arrest the development of hypotension.

The second group of animals dived to 230 ft (8 bar) were observed specifically for cord DCS using SEPs. The dive details are shown in Table 12. The 10.1 - 13.0 kg group had similar onset times to the first group with 3 min for dives > 51 min and 9 min for shorter dives. Experience with severity and controlling dives was the same.

The inability to return to the surface within a short time demonstrated a wide variation in the severity of the systemic DCS, so a dive profile producing less variance in severity of DCS was sought.

TABLE 12

FORM AND OUTCOME OF FIRST DIVES TO 230 FSW (8 bar)

Wt group (kg)	n	$\bar{x}$ bottom time (range) to give DCS (min)	Ascent Rate ft min^{-1}	Controlling Dives	Cord DCS	DCS
< 10	3	61.0 (57-65)	51	2	2	2
10.1-13	5	50.6 (47-55)	60	4	1	4
> 13	8	46.9 (37-50)	56	5	5	6

TABLE 13

FORM AND OUTCOME OF FIRST DIVES TO 300 FSW (10 bar)

Time group (min)	n	$\bar{x}$ weight (kg)	Ascent Rate ft min^{-1}	Controlling Dives	Cord DCS	DCS
6	5	10.8	55	2	3	4
10 - 15	8	13.0	57	2	5	6
> 17	2	14.3	57	0	0	2

The final model was a short air dive to 300 ft (Table 13). The derivation of this is described in the discussion. The first dives were for 6 min but bottom times up to 22 min were explored. Bottom times of between 10 and 15 min for dogs of all weights, resulted in more moderate DCS which allowed the dogs to be kept on the surface for a period preceding the start of treatment. Twelve out of 15 dogs developed DCS and eight of these went on to develop cord DCS after one dive. Three out of four dogs redived for shorter times developed cord DCS. Only four dogs were given controlling dives with decompressions of 10 min or less. They were all successfully returned to atmospheric pressure before treatment. Only one of these was recompressed because of major cardiovascular pressure changes. The remainder were recompressed to stop ECG abnormalities (2) and to stop a precipitous reduction in EEG amplitude (1).

The nature and timing of the onset of DCS from the two dives was remarkably similar (Table 14). However, the degree of severity was markedly different because, unlike the 300 ft (10 bar) dives, most of the 230 ft (8 bar) dives resulted in a controlling recompression to halt the development of the disease process. This frequently resulted in the dogs being held at pressure to prevent further deterioration.

Notable differences in the results of the two dives are that the 300 ft (10 bar) dives, even without a controlling recompression, did not usually cause uncontrollable hypotension (systolic AoP < 100 mg Hg) and the degree of EEG amplitude loss was very much less. There was a similar incidence of cord DCS from both dives.

The principal feature of the onset of DCS following both dives

TABLE 14

THE OCCURRENCE AND ONSET TIMES OF CHANGES IN MEASURE PARAMETERS

DIVE DEPTH	230 ft 12/12 (+ 3 redived)			300 ft 12/15 (+ 1 redived)		
DCS	FIRST DIVE	TOTAL	FIRST DIVE ONSET TIME $\bar{x}$ (range)	FIRST DIVE	TOTAL	FIRST DIVE ONSET TIME $\bar{x}$ (range)
RVP ↑	3/9	3/9	17.0 (2 - 29)	4/8	5/8	11.2 (6 - 18)
CSFP↑	9/12	10/12	10.3 (1 - 26)	9/10	10/10	7.6 (1 - 12)
EEG ↓ (3)	10/12	10/12	4.2 (1 - 11)	9/12	9/12	8.7 (1.5 - 24)
CEP ↓	11/12	12/12	11.1 (4 - 38)	11/12	12/12	9.9 (5 - 18)
SEP ↓	8/12	10/12	17.1 (6 - 38)	8/12	9/12	12.0 (2 - 27)
AoP ↓	4/12	6/12	18.3 (4 - 33)	0/12	0/12	- (-)
AoP ↑ (1)	2/12	4/12	9.0 (9 - 9)	3/12	4/12	8.7 (5 - 15)
RVP+CSFP↑(s)	3/9	3/9	16.0 (2 - 29)	4/8	5/8	9.2 (1 - 18)
EEG No CSFP↑	2/12	3/12	7.0 (3 - 11)	0/10	0/10	- (-)
CSFP↑alone (2)	3/9	4/9	9.0 (1 - 13)	3/8	3/8	8.1 (5.7 - 12)
ECG Δ	1/12	2/12	3.0 (3)	4/12	4/12	11.5 (3 - 20)

(1) AoP↑ when it occurs is always associated with ↑ RVP and CSFP

(2) CSFP ↑ sometimes precedes RVP ↑ but CSFP is always ↑ if RVP is ↑

(3) EEG↓ in 300 ft dives was much less severe than 230 ft dives

One case of chokes in each group. When the denominator is less than n for the group, it indicates that the relevant data were only available for the number shown. these numbers represent what were considered to be major and therefore pathological changes.

was a loss of EEG amplitude and a rise in CSFP in at least 75% of cases. A rise in RVP was often seen a little later in about half of the cases. A rise in RVP resulted in a simultaneous rise in CSFP. When aortic pressure increased significantly RVP was usually already elevated. Such an increase in AoP was never sustained and the subsequent fall sometimes dropped systolic AoP below 100 mm Hg. The elevation of RVP and CSFP generally fell towards pre-onset levels within 20 min of their peak. Of all dogs with indications of DCS those with cord DCS were indistinguishable from those without. Two dogs had a rise in CSFP without changes in SEP becoming evident. Occasional ECG changes were seen. These included arrhythmias, conduction defects, and signs of myocardial ischaemia. Repeat dives of shorter duration than first dives generally resulted in earlier changes of greater severity but were no guarantee of cord DCS. The extent of physiological changes is shown in Table 15. In those cases were arterial blood could be taken during DCS, evidence of hypoxaemia, hypercapnic acidosis and plasma loss (packed cell volume increased by up to 12%) were seen. It became routine to correct an assumed plasma volume loss of 8% with Ringers Lactate.

Two examples of the diagnosis of spinal cord DCS using evoked potentials are shown in Figure 16. Initial changes were commonly amplitude losses in the late small waves. This progressed to affect the earlier large waves and could reach the stage of reducing the SEP to an isoelectric voltage. Sometimes there was a generalised attenuation affecting all the travelling waves in the affected cord region. With few exceptions, changes in SEP amplitude were detected by eye well before they reached a decrement in cumulative amplitude of 10 percent.

The anatomic distribution of the cord lesions was the same in both groups and overall 16 lumbar cord lesions and seven cervical cord lesions were identified.

TABLE 15

CONTROL DATA AND MAXIMUM DEVIATIONS FROM CONTROL VALUES DURING THE PRETREATMENT PHASE OF DECOMPRESSION SICKNESS RESULTING FROM SINGLE DIVES TO THE DEPTHS SHOWN

DIVE DEPTH	230 fsw	300 fsw
CONTROL $\bar{x}$ ± SD (Systolic/Diastolic)		
AoP mm Hg	136 ± 12/110 ± 10	136 ± 22/106 ± 16
RVP mm Hg	25 ± 8/ 0 ± 1	16 ± 6/ 0 ± 1
CSFP mm Hg	7 ± 3/ 6 ± 3	5 ± 4/ 3 ± 3
HR min^{-1}	128 ± 27	118 ± 17
MAXIMUM CHANGE $\bar{x}$ ± SD (range) n		
AoP ↑ Systolic	52 ± 44 (10 - 110)4	60 ± 39 (15 - 95)4
Diastolic	41 ± 29 (5 - 70)4	31 ± 23 (0 - 55)4
AoP ↓ Systolic	24 ± 12 (10 - 50)8	27 ± 14 (14 - 45)8
Diastolic	18 ± 16 (0 - 25)8	24 ± 7 (15 - 35)8
RVP ↑ Systolic	16 ± 9 (6 - 28)4	15 ± 7 (8 - 25)4
Diastolic	6 ± 7 (0 - 13)4	5 ± 10 (-1 - 20)4
CSFP ↑	19 ± 12 (4 - 36)9	12 ± 9 (5 - 37)10
HR ↑	15 ± 9 (6 - 30)6	20 ± 10 (8 - 32)5
HR ↓	22 ± 12 (15 - 36)3	11 ± 5(8 - 15)2

The data are drawn only from those dogs in which the parameter changed beyond normal variation.

5.4 DISCUSSION

There are other dive profiles which have been shown to cause DCS in dogs. The original discovery of the double dive method, where the cardiopulmonary DCS caused by the first dive (146 ft (5.4 bar) for 105 min with decompression in 6 s) was treated by a second shallower dive and commonly resulted in cord DCS, was made by Behnke et al. (1937). This also entailed a long decompression. McIver and Leverett (1964) and Cockett et al. (1967) used a 165 ft (6 bar) dive for 60 min with decompression at 16 ft min^{-1}. This produced classical cardiopulmonary DCS which could be controlled by recompression to 66 ft (3 bar) (McIver and Leverett. 1964) and had a high mortality rate with brain and cord pathology if untreated (Cockett et al., 1967).

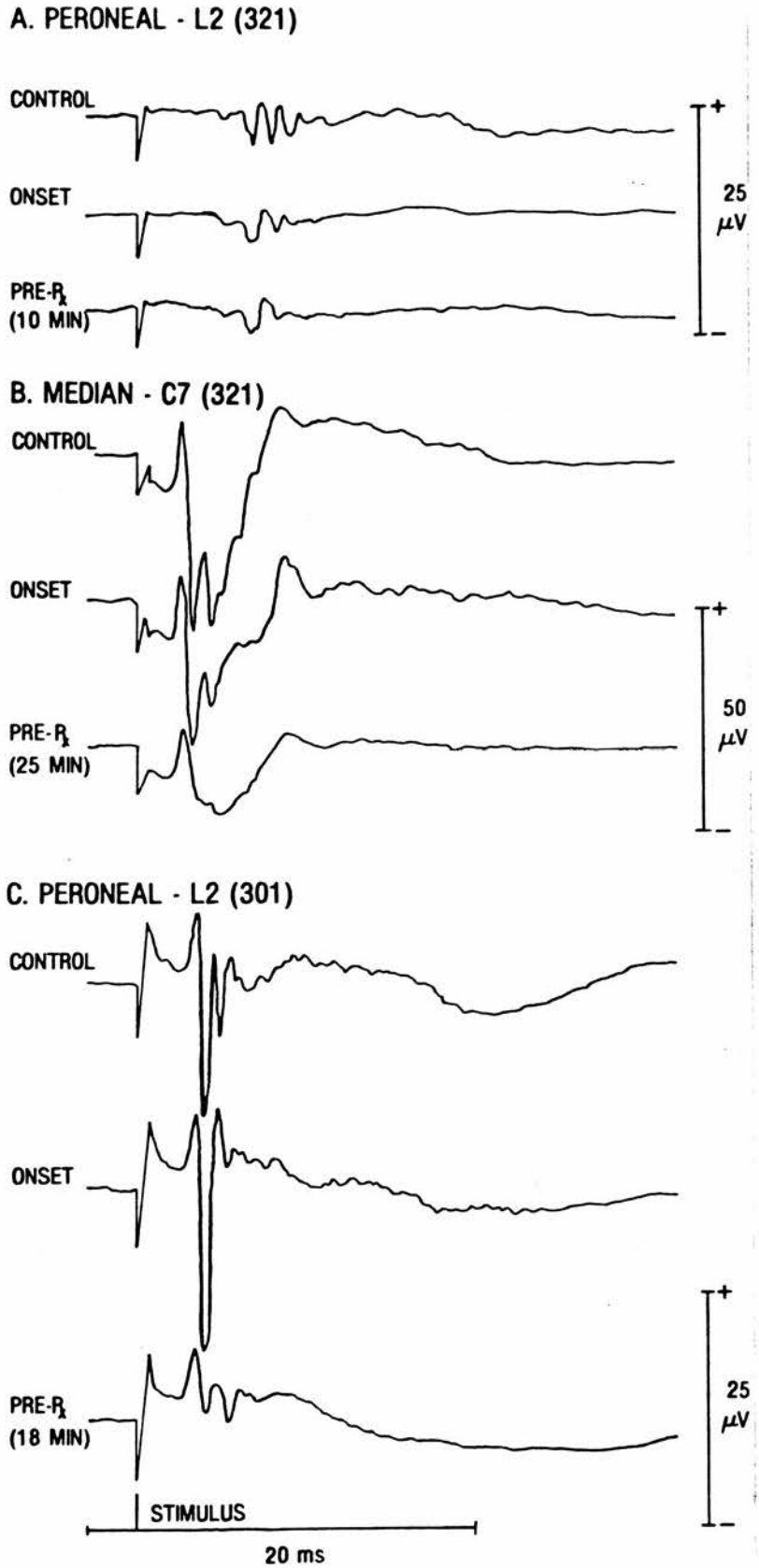


Figure 16. Spinal evoked potentials in decompression sickness. Three examples of SEP changes at the stages shown. A and B are from the same dog, which had been dived to 300 ft. Sample C came from a 300 ft-dive dog.

The same or longer dives with decompression of 2.25 to 5.25 min resulted in paralysis and shock. There was one instance of probable cerebral DCS and all animals had to be sacrificed inside 10 to 15 min (Wolkiewiez et al., 1979). A 50 min oxy-nitrogen dive with an equivalent air depth of 240 ft (8.3 bar) ending in a decompression lasting 10 min, resulted in death in 10/18 dogs within minutes of surfacing (Wells et al. 1971). Arturson and Grotte (1971) lost 2/7 dogs after 60 min dives to 200 ft (7 bar) with a bleed decompression lasting about 12 min. All of these dives created the conditions which might lead to cord DCS, but all resulted in very severe systemic involvement with a high risk of circulatory collapse.

Bove et al. (1974) reported a dog decompression sickness model which entailed a 220 ft (7.7 bar) dive of 40 min. With the standard compression and decompresssion rates, these dives commonly led to severe cardiopulmonary embarrassment. This was usually associated with signs of pulmonary vascular obstruction. Rapid recompression to 70 ft allowed the condition to stabilise before a decompression lasting up to 45 min returned the dogs to the surface. During this phase cord DCS became evident. There were several variations on the basic theme including longer dives, a 5 min stop at 40 ft, and a slow decompression from there to the surface.

That dive schedule was modified by rounding it to 8 bar (230 ft), and refined by reducing the bottom time in inverse relation to weight group, to a duration just exceeding that which would give around a 90% chance of cord DCS within about 20 min of surfacing. Almost every case produced by these dives required a controlling dive to prevent cardiopulmonary collapse. Initially it was planned to allow the cord DCS to consolidate for an hour before starting treatment. However, experience showed that after 20 min from the time of diagnosis very little SEP amplitude would be recovered. Generally, it was not possible to return dogs to atmospheric pressure within 20 min of the onset which resulted in their being held at any pressure between 2 and 40 ft. This indicated a wide range of severity, clearly not a good position from which to try and compare the efficacy of different treatments.

An additional complication with this model was a very high incidence of cerebral DCS as indicated by the loss of EEG. It seems unlikely that the small difference between the 230 ft (8 bar) dive and that reported by Hallenbeck et al. (1975) could account for the latter's failure to observe cerebral DCS. The principal difference may have been posture. Their animals were all lying down either prone or on their sides while the dogs in this study were all prone but with head held erect. The EEG loss was one of the earliest signs, often preceding any indications of pulmonary vascular obstruction seen as a rise in RVP. It often occurred without a significant rise in CSFP which would indicate venous obstruction in the drainage from the neuraxis. Two dogs were dived on their sides and while they both developed DCS neither experienced a loss of EEG. This postural difference in outcome suggests that bouyancy might be aiding the distribution of arterial bubbles in a cerebral direction as in arterial gas embolism. It appears therefore, that the most common first signs of DCS in this model might result from arterial gas. This is not to say that the gas did not originate in the venous return and pass through the pulmonary vasculature. Sufficiently small bubbles may well traverse the pulmonary filter (Butler and Hills, 1979). Extravascular bubble formation is also a possibility.

While there was the possibility of avoiding EEG loss by a change in posture, the practical problems such a change created in securing of the cord electrodes, prevented that route being taken.

It was possible to produce changes in the SEPs by artificially causing the epidural vertebral venous system (EVVS) to be obstructed by bubbles. Taking an anaesthetised dog to 20 ft and inflating a balloon in the inferior vena cava caused venous return to shunt through the azygous system and the EVVS. Injecting 20 ml (at 1 bar) or air into a femoral vein during the decompression and then deflating the balloon caused some air to be trapped in the EVVS and shortly after surfacing gave rise to SEP changes similar to those seen in DCS. A similar effect was produced by retrograde injection of air into the azygous vein during decompression. At autopsy there was air in the EVVS and associated haemorrhage. The disadvantage of such a

model, which was developed for other purposes, was that there was no reservoir of inert gas in solution in the tissues.

In studies of the treatment of arterial gas embolism (AGE) it had been observed that certain combinations of air pressure and time, led to impairment of cord blood flow on decompression from dives which would not normally be expected to cause cord DCS in dogs (Leitch et al., 1984). This suggested that a small volume of gas, injected into a femoral artery before a short deep dive might, by either seeding or redistributing, lead to cord DCS without such severe systemic disturbances as a longer dive would cause. It needed not less than 5 ml of air, given within 5 min of the start of a dive of 15 to 20 min at 230 ft, to cause changes after decompression. There were few systemic disturbances and out of six dogs a loss of EEG was seen in two, a severe loss of SEP in one and small changes in SEP in four. The injection of air into the femoral artery before diving had two possible routes to the neuraxis. On compression it would be cleared through the limb into the venous drainage. Being bouyant some of the bubbles could enter the venous anastomoses and reach the EVVS, there to later expand and also take up dissolved gas on decompression. Other bubbles would return to the heart and those not caught in the lungs would then be free to enter the arterial distribution. At this point, bubbles would be small enough to pass freely through capillaries. It would therefore be possible for some to end up in the relatively sluggish blood pools of the EVVS (Batson, 1940) only to grow on decompression. This model was discarded because of its unnatural origins and high rate of cerebral involvement.

The source of the problem of severe systemic involvement lay in the volume of gas released into the circulation. Theoretically, if the critical tissues could be saturated quickly, i.e. the neuraxis and epidural fat, with sufficient gas to cause DCS, the tissues with longer half times would contribute proportionately less gas on decompression. Thus, the systemic problem might diminish. Therefore deeper and shorter dives were tried at a 300 ft (10 bar) dive and a range of bottom times between 6 and 22 min was explored. There was a high incidence of cord DCS but systemic disturbances were much

less severe than with the 230 ft (8 bar) dives, as indicated by the fact that all 300 ft dogs were returned to the surface and kept there prior to treatment. The onset times and form of DCS were the same as in the earlier dives, but a much more economical and controllable model of cord DCS which was suitable for the comparison of treatments was available. All subsequent work was done with dives of between 12 and 15 min duration. A dive to 300 ft, breathing air, with descent time of 4 min and an ascent rate of 60 ft min^{-1} to 60 ft and 45 ft min^{-1} from 60 ft to the surface can be expected to have at least a 75% success rate in producing cord DCS. A repeated dive of 9 + min generally caused cord DCS in the remainder. Interestingly, comparing the human decompression schedules for the two types of dives, shows that the decompression time from a 230 ft (70 m) for 45 min dive is two to three times that from a 300 ft (90 m) for 15 min dive (Royal Navy, 1972; US Navy, 1973). The 230 ft dives, because of their severity, should perhaps be considered more akin to "blow-up", the uncontrolled surfacing from a dive requiring decompression stops. This type of model would therefore be more appropriate for the study of "blow-up".

SECTION 6

PRELIMINARY STUDIES OF FACTORS IN TREATMENT

PRELIMINARY STUDIES OF FACTORS IN TREATMENT

6.1 PREAMBLE

Prior to starting the main study the experimental scheme was tested using for the most part two of the commonly used standard treatments. The objective was to ensure that some recovery would occur, and that it could be monitored through the SEPs. This led to the establishment of an appropriate time interval between the diagnosis of cord DCS and the start of treatment.

6.2 METHOD

Sixteen of the dogs previously described, which remained physiologically stable and had unequivocal cord DCS (4 cervical and 15 lumbar lesions) according to the evoked potential (EP) observations, were treated by recompression. Delays between the diagnosis of cord DCS and treatment were not less than 9 min but could have been as much as 25 min. The maximum time is uncertain because of varying intervals between the last normal and first abnormal SEP.

The treatments used were the standard options of 60 ft (2.8 bar) with oxygen, or 165 ft (6 bar) with air, but 165 ft with 47% oxygen (PO_2 2.8 bar) and 230 ft with air were also included. The appropriate gases were supplied to the ventilator before recompression. The earlier studies having shown that EPs were unaffected by continuous exposure to 2.8 bar of oxygen in dogs without DCS, the treatments using increased concentrations of oxygen were given without break for two hours.

Compression rate to the treatment depth was between 60 and 80 ft min^{-1}. The experiment was terminated after 120 min at the treatment depth. Each experiment was based for time on the first cord lesion diagnosed. Evoked potential recording was repeated continuously until the start of compression. Each series of EPs was repeated twice in the first 15 min at pressure and thereafter at 15 min intervals for each series observing a lesion, and at 30 min intervals in series observing normal cord. For example, a lesion in the lumbar cord

would be observed with the peroneal inputs every 15 min, while the normal median-cervical cord would be checked at 30 min intervals with the median input.

The last pretreatment observation was made close to the time of leaving the surface for treatment. This result was converted to express it as the percent lost of mean control SEP amplitude. If there was a further reduction in SEP at the start of treatment this SEP was used instead of the pretreatment SEP. Because the severity of the lesions was both unpredictable and uncontrollable, it was considered that some normalising procedure should be applied. This was done by expressing all recovery as a percentage of what was lost. This did not alter the trends observed when looking at straight percentages of control but did reduce the variance of the groups. This system was used for all subsequent experiments.

All results are expressed as the mean ± 1 standard deviation and statistical analysis was by one way analysis of variance.

The method for producing global CNS ischaemia described by Hallenbeck and Bradley (1977) was used to study the effects of acute cord ischaemia and the restoration of blood flow on SEPs. The three dogs studied were prepared as previously described. The ischaemia was caused by raising the hydrostatic pressure of the CSF space by means of a bottle of Elliotts solution B (Elliott and Jasper, 1949) suspended at a variable height sufficient to exceed mean arterial BP. The solution was heated to 38°C before reaching the adaptor attached between the cisternal needle and the pressure transducer. The hypertensive Cushing response was blocked by phentolamine (10 mg i.v.) and BP was controlled by the removal and return of blood. The CSFP was raised for various periods between 13 and 20 min and then restored to normal while SEP recovery was observed.

6.3 RESULTS

Of the 16 dogs used in this study, nine were exposed to 230 ft (8 bar) and seven to 300 ft (10 bar) dives; of these 4 + 3 respectively were treated with oxygen at 60 ft (2.8 bar) and 3 + 3 with

air at 165 ft (6 bar). Two of the 230 ft dogs were treated with air at 230 ft and the remaining 300 ft dog with 47% oxygen in nitrogen at 165 ft. Three dogs from the 230 ft dives each had two distinct sites of cord DCS which were observed separately. These dogs were distributed one to each treatment.

Eight dogs from the 230 ft dives were held at pressures between 5 and 40 ft before treatment (mean pressure 25 ft). All other dogs were held at surface pressure. There was a variable interval between the last recorded normal SEP and the observation leading to recognition of a lesion. This led to some uncertainty about the duration of lesions before treatment. Possible ranges of duration began with a known minimum and a possible maximum. They were 12.5 ± S.D. 5.8 to 18.7 ± 3.9 min for the 230 ft dogs and 15.0 ± 7.0 to 21.9 ± 7.4 min for the 300 ft dogs.

The principal physiological measurements are shown in Table 16. There was a tendency for mean BP and cerebral perfusion pressure (CPP) to be higher in the 300 ft dogs than the 230 ft dogs. This may reflect the different amounts of Ringers Lactate and bicarbonate solutions given between the onset of DCS and the completion of treatment. These were 287 ± 126 ml and 204 ± 61 ml respectively. In general, right ventricular pressure (RVP) and CSFP were a little lower than their early DCS peaks by the start of treatment and changed little thereafter. No differences were observed between treatments or between original dives. The previously mentioned ECG changes were generally reversed by recompression but EEG never recovered.

Two examples of the response of lumbar SEPs to treatment with oxygen at 60 ft are shown in Fig. 17. The causative dives were both to 300 ft. Dog 103 required a controlling dive. By the start of treatment they had lost 92% and 84% of their control amplitude, respectively. Of this loss dog 102 progressively recovered 44% by 114 min of treatment. Dog 103 quickly recovered 48% by 16 min and then steadily deteriorated until by 88 min the SEP was smaller than the pretreatment level.

The change in summed EP amplitude permitted before a diagnosis was made, ranged from 0 to 16%. The mean change allowed to pass, for the 230 ft dogs was 0.6 ± 1.6% and for the 300 ft dogs was 4.8 ± 7.2%.

TABLE 16

PHYSIOLOGICAL MEASUREMENTS BY CAUSATIVE DIVE AND TREATMENT

DIVE		230 ft				300 ft			
Parameter		$\overline{BP}$	RVP_{sy}	$CSFP_{sy}$	CPP	$\overline{BP}$	RVP_{sy}	$CSFP_{sy}$	CPP
R	Phase								
60 ft	Pre R	104	28	15	89	114	27	16	99
		±28	±9	±4	±25	± 4	±15	±3	±7
O_2	5	80	26	15	65	105	28	23	85
		±13	±2	±6	±9	± 3	±29	±2	±42
	60	83	13	14	68	108	22	17	90
		±14	±2	±8	±14	±15	±15	±8	±13
	120	77	14	14	63	111	43	13	101
		±17	±1	±10	±18	±17	±24	±8	±14
165 ft Air	Pre R	106	10	16	90	94	11	6	88
		± 5	±0	±3	±6	±14	±2	±2	±16
	5	89	11	17	73	107	36	17	89
		±16	±1	±10	±22	± 9	±14	±7	±9
	60	90	10	15	74	113	19	22	88
		± 3	±2	±11	±12	±18	±12	±13	±43
	120	86	14	15	71	109	23	21	88
		± 8	±5	±9	±14	±34	±10	±9	±43
Other*	Pre R	89	25	11	78	70	8	8	62
		±32	±8	±1	±33	-	-	-	-
	5	90	30	30	59	128	14	17	111
		±28	-	±22	±50	-	-	-	-
	60	90	12	27	62	92	22	22	70
		±42	-	±26	±69	-	-	-	-
	120	70	12	25	46	95	20	18	77
		±56	-	±12	±66	-	-	-	-

Mean ± 1 SD for mean arterial pressure ($\overline{BP}$), systolic RVP, systolic CSFP and cerebro-spinal perfusion pressure (CPP). Values given for the stated times before and during treatment. * 'Other' includes 2 dogs in the 230 ft group which were treated at 230 ft with air and 1 dog in the 300 ft group which was treated with 47% O_2 at 165 ft.

TABLE 17

SEP LOSS AND RECOVERY BY CAUSATIVE DIVE AND TREATMENT

DIVE (ft)		230	300	230 + 300
Treatment and Phase				
60 ft O_2	Loss(n)	51.0±16.7 (5)	77.1±23.7 (3)	60.6±22.4
R	15 min	18.4±25.8	36.2±17.0	25.1±23.4
	40	34.0±45.2	19.2±22.0	28.4±37.0
	80	39.3±39.4	25.1±23.9	33.9±33.3
	120	25.3±34.7	24.0±22.4	24.8±28.8
165 ft A	Loss(n)	53.9±12.9 (4)	77.6±11.1 (3)	64.1±16.9
R	15 min	00.0±00.0	39.1±16.1	16.7±22.9
	40	13.2±21.1	30.4±19.7	20.6±20.9
	80	16.0±20.8	30.7±18.3	22.3±19.7
	120	18.6±21.5	32.8±13.2	24.7±18.6
Other	Loss(n)	56.1±21.9 (3)	68.7 - (1)	59.3±18.9
R	15 min	28.4±49.2	14.6 -	24.9±40.7
	40	35.2±44.4	6.4 -	28.0±39.0
	80	45.7±51.2	0 -	34.2±47.6
	120	43.1±47.0	0 -	32.3±44.0
All	Loss	53.2±15.4	76.1±15.3	
R	15 min	14.8±28.6	34.4±16.2	
	40	27.3±36.5	22.2±19.3	
	80	33.0±36.3	23.9±20.5	
	120	27.5±32.6	24.4±19.0	

Mean ± SD. Percent lost before treatment and percent of loss recovered at the stated times during treatment.

The SEPs deteriorated between the last surface measurement and early treatment in seven of the 230 ft dogs and one of the 300 ft dogs. The two dogs in the 230 ft groups which did not show a fall in SEP at this stage included the one dog not held at pressure. A similar proportion of SEPs in both groups deteriorated by more than 5% from their best recovery; nine out of 19 SEPs overall. There was no recovery at any stage in four of the 230 ft group SEPs. By the end of treatment 6/12 and 2/7 SEPs showed no recovery in the 230 and 300 ft groups respectively.

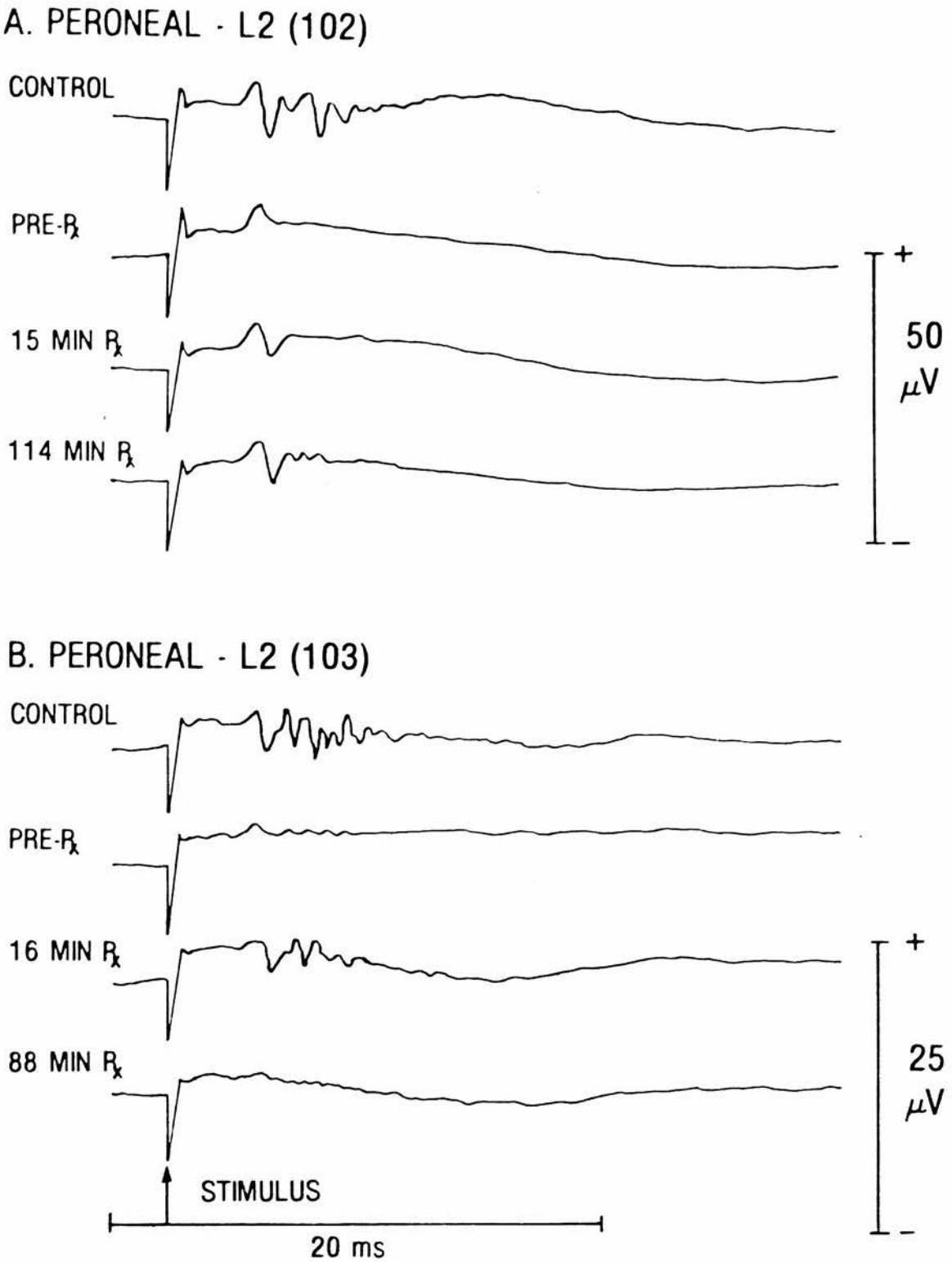


Figure 17. The effect of treatment on spinal evoked potentials lost during decompression sickness. Treatment was with oxygen at 60 ft. Dog A lost 92% of its SEP before treatment. It recovered 17% by 15 min and 44% of its loss by 114 min. Dog B lost 84% of its SEP before treatment. It recovered 48% of its loss by 16 min before deteriorating to a condition worse than its pretreatment state.

Recovery ranged as high as 100% transiently in two SEPs. The severity of the lesions and their recovery are shown by dive and treatment in Table 17. The severity of SEP loss from the two dives at 53.2% and 76.1% respectively, was significantly different $P < 0.01$. However there was no difference in recovery either in treatments or dives in this study. Overall mean recovery was around 25%, most of which was attained within about 15 min.

There was an insignificant difference in mean delay time between those with zero recovery at 15 min and the rest: 17.10 ± 5.39 min and 15.50 ± 6.02 min respectively. Similar times were seen for the same comparison at 120 min: 17.75 ± 2.49 min and 15.33 ± 6.87 min respectively. However, when SEP recovery at 120 min was compared between groups with a maximum possible delay to treatment of < 19 and > 20 min, a significant difference was found ($P < 0.05$) with SEP recoveries of 40.6 ± 28.2% and 16.4 ± 19.9% respectively.

No predictors for a greater likelihood of recovery were seen in the physiological observations or treatments. Only the interval to treatment appeared to be of importance.

Three dogs were subjected to a total of four episodes of global CNS ischaemia. It was observed that the cortical EPs were lost within one minute of the step increase in CSFP. Thereafter sub-cortical FFPs were progressively lost in a centrifugal fashion until nothing remained after about 15 min. With ischaemia as long as 13 min no restoration of the cortical waves was seen in a 30 min recovery period, although most FFPs returned, even after 17 min of ischaemia.

The SEPs sometimes exhibited a sudden transient increase in amplitude in the first minute of ischaemia. Some loss of amplitude in the travelling waves occurred between 4 and 5 min and progressed until the early root entry potential was all that remained by 7 to 12 min. This too was lost after 15 to 17 min.

Restoration of blood flow after 13 - 20 min of ischaemia allowed varing degrees of SEP recovery in 25 to 30 min of observation. The

majority of the return had occurred after 5 min of reflow. After ischaemia of 15 or more minutes duration, SEP recovery in the observation period ranged from 50 to 90% of pre-ischaemia amplitude.

6.4 DISCUSSION

The only physiological difference between either groups or treatments was the higher mean BP in the 300 ft group. This was probably the result of a greater infusion of fluid.

There was a surprisingly high incidence of continued SEP deterioration into the first few minutes of treatment in the 230 ft group. Some of these were doubtless due to an unduly long interval between the last record and the start of treatment, so were artifacts. However, the remainder were seen where the interval was brief. These findings may reflect the fact that many animals in the group were held at pressure and so on treatment, particularly at 60 ft, experienced less compression than the 300 ft group, and therefore, initially less effective treatment with the result that the lesions continued to develop. Six of the eight SEPs which showed no improvement by the end of treatment were also held at pressure before treatment. The holding at pressure of the 230 ft group was probably also responsible for the smaller SEP loss seen in this group.

Only three SEPs showed better than 50% recovery, eight better than 30%, and eleven better than 20%. Overall recovery was in the region of 25%. Late deterioration was commonly seen. No treatment produced better results than any other. These findings indicate that this series contained conditions suitable for the study of delayed therapy. The frequency of secondary deterioration suggests that chemotherapy might be an appropriate additional measure. The key factor to recovery lay in the length of delay before treatment. With an interval of 15 to 18 min between diagnosis and recompression, there was little chance of achieving complete restoration of the SEP. The frequency of secondary deterioration in the short time of 120 min without associated decompression strongly suggests vascular involvement in the mechanism.

The global ischaemia studies indicated that, following a sudden cessation of cord blood flow, except for a sudden transient increase in amplitude, the travelling waves of the SEPs remained unchanged for between 4 and 5 min. Thereafter, function rapidly faded until totally absent in 15 to 17 min. If flow was restored after 20 min of ischaemia then a large part but not all of SEP amplitude returned inside 30 min. The continued function lasting 4+ min after the onset of ischaemia would suggest that in this model of DCS a diagnosis was made not less than 5 min after flow had been compromised. Therefore, if the cessation of function is the result of vascular obstruction and there is a 15 min delay it would mean an ischaemic episode of 20 min duration.

The results of delayed treatment of cord DCS appear to be exactly in keeping with what would be anticipated from studies of cord ischaemia where the insult was present for about 20 min. It was concluded that an appropriate interval between the diagnosis of cord DCS and the start of treatment would be about 15 min. This would be unlikely to allow complete recovery in the proposed 2 hour treatment period.

SECTION 7

THE RELATIONSHIP BETWEEN SPINAL CORD BLOOD FLOW AND EVOKED POTENTIALS IN DECOMPRESSION SICKNESS

THE RELATIONSHIP BETWEEN SPINAL CORD BLOOD FLOW AND EVOKED POTENTIALS IN DECOMPRESSION SICKNESS

7.1 PREAMBLE

An experimental model of a condition largely attributed to vascular obstruction, which was to be diagnosed and monitored by means of evoked potentials, necessitated the establishing of a correlation between cord blood flow and changes in SEPs. The requirement was to demonstrate that SEP changes only occurred after changes in cord blood flow. Such a demonstration would be the definitive validation of a method using evoked potentials as a means of diagnosis in this model of DCS.

7.2 METHOD

Seven dogs weighing 7 - 15 kg were prepared in the standard fashion and with the additional arterial catheter required for the flow study.

One dog was prepared and maintained in the prescribed fashion for about 2 hr, during which time it wasstimulated for EP recording. A 1-min autoradiographic flow study performed on this undived dog served as a control. Three dogs (80J, 86J, 88J) were used in EP control studies at 60 and 165 ft, en route to 230 ft. They remained at 230 ft for 45 - 60 min before decompression to the surface. The other three dogs (38R, 86P, 88P) were used in a different set of EP control studies of helium breathing as deep as 300 ft. They were decompressed from these dives without incident. After a surface interval they were dived to 165 ft breathing air via a 15-min stage at 60 ft. After 120 min at 165 ft they were decompressed to 60 ft, where they remained for 10 min before returning to the surface.

After surfacing the SEPs were continuously recorded until various degrees of DCS were observed. A one minute ^{14}C-iodoantipyrine autoradiographic flow study was then performed. The observations sought were low cord blood flows where white and grey matter flows were less than 6 and 15 ml 100 gm^{-1} min^{-1}, respectively, flows that are considered to be "neuron-disabling" in the brain (Branston et al., 1974, Hallenbęck et al., 1982).

7.3 RESULTS

The six dived dogs developed DCS of varying severity. Four showed a rise in CSFP of between 8 and 70 mm Hg, and three showed a rise in RVP of between 24 and 60 mm Hg. Four showed gross SEP changes and two showed small variable changes. Only two showed gross EEG changes, one of which (88J) became isoelectric.

The mean cord blood flows in the control dog were 11 and 38 ml 100 gm^{-1} min^{-1} for white and grey matter, respectively, with ranges of 6 - 16 and 29 - 46 ml 100 gm^{-1} min^{-1}. This compared with previously observed control values for lumbar white and grey matter flows of 8 and 21 ml 100 gm^{-1} min^{-1}, with ranges of 6 - 11 and 15 - 26, respectively, in dogs not experiencing peroneal nerve stimulation (Leitch et al., 1984b).

Relevant autoradiographs of cortical blood flows are shown in Figure 18, where the top half of 88P may be regarded as normal. Examples of cord flows in cervical, upper and lower thoracic, and lumbar regions are shown in Figure 19, together with details of high and low flows in grey and white matter, and amplitude of SEP.

80J (Figures 20 and 21).

There were few systemic changes, with only a small increase in CSFP, a stable BP and no gross changes in EEG. Transient lumbar SEP changes showing alternating increases and reductions of amplitude occurred between 9 and 67 min post-dive (Figure 20). No change in median-cervical SEP was seen at 58 min post-dive. A correspondence between SEP and CEP (Figure 21) amplitudes was seen at 28 and 36 min. The cord flow study done 13 min after the last EP recording showed no evidence of "neuron-disabling" flows, but several instances of abnormally high flows, particularly in the lumbar region (Figure 19). The cortical autoradiograms (Figure 18) revealed no clear evidence of low flows, but again, evidence in some areas of high flows. Overall, the section does not appear normal when compared with the upper sections of 86P.

86J (Figure 22)

CSFP was elevated shortly after surfacing and cycled throughout 50 min of observation, reaching 90 mm Hg at its highest point. There

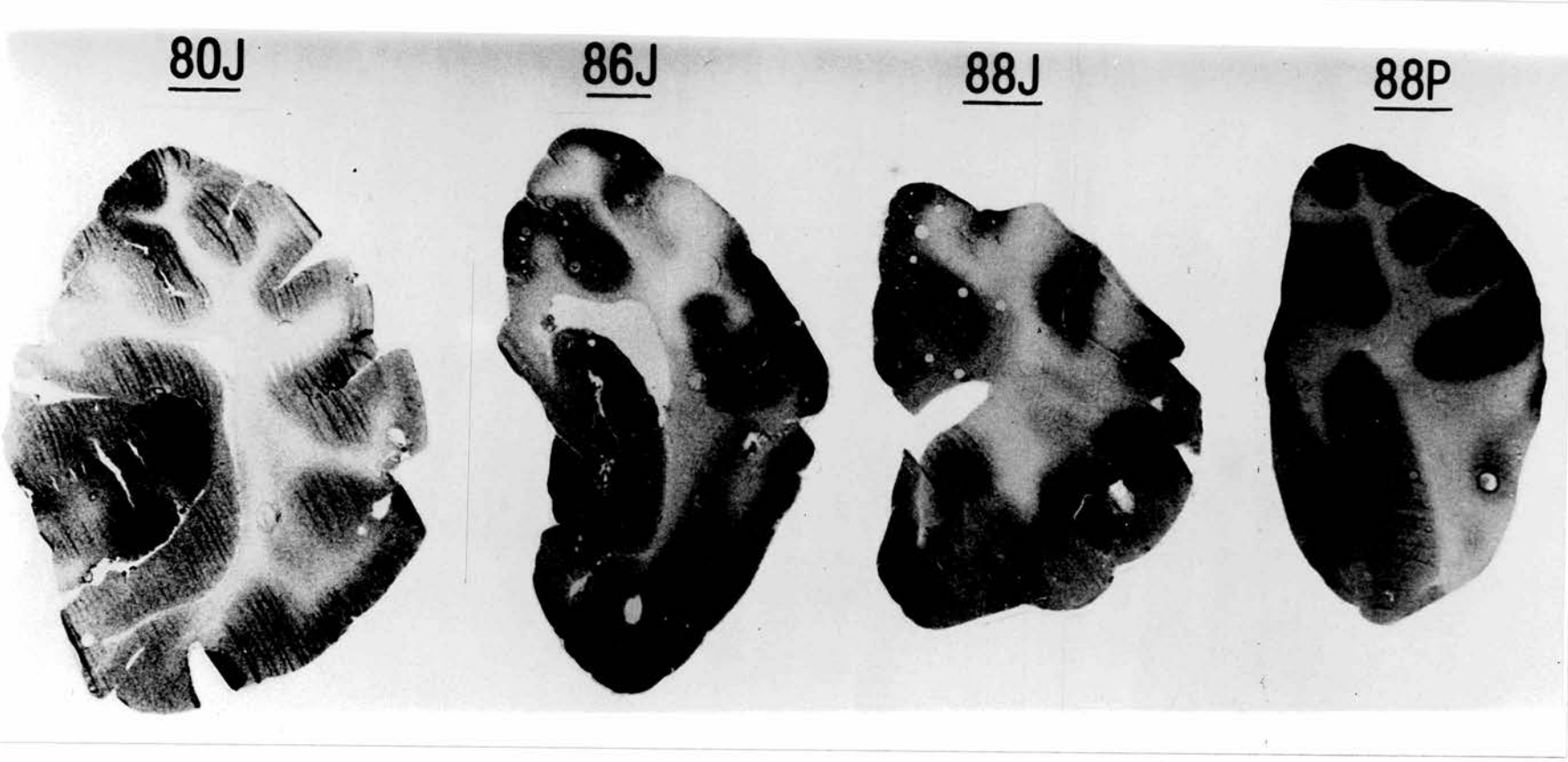
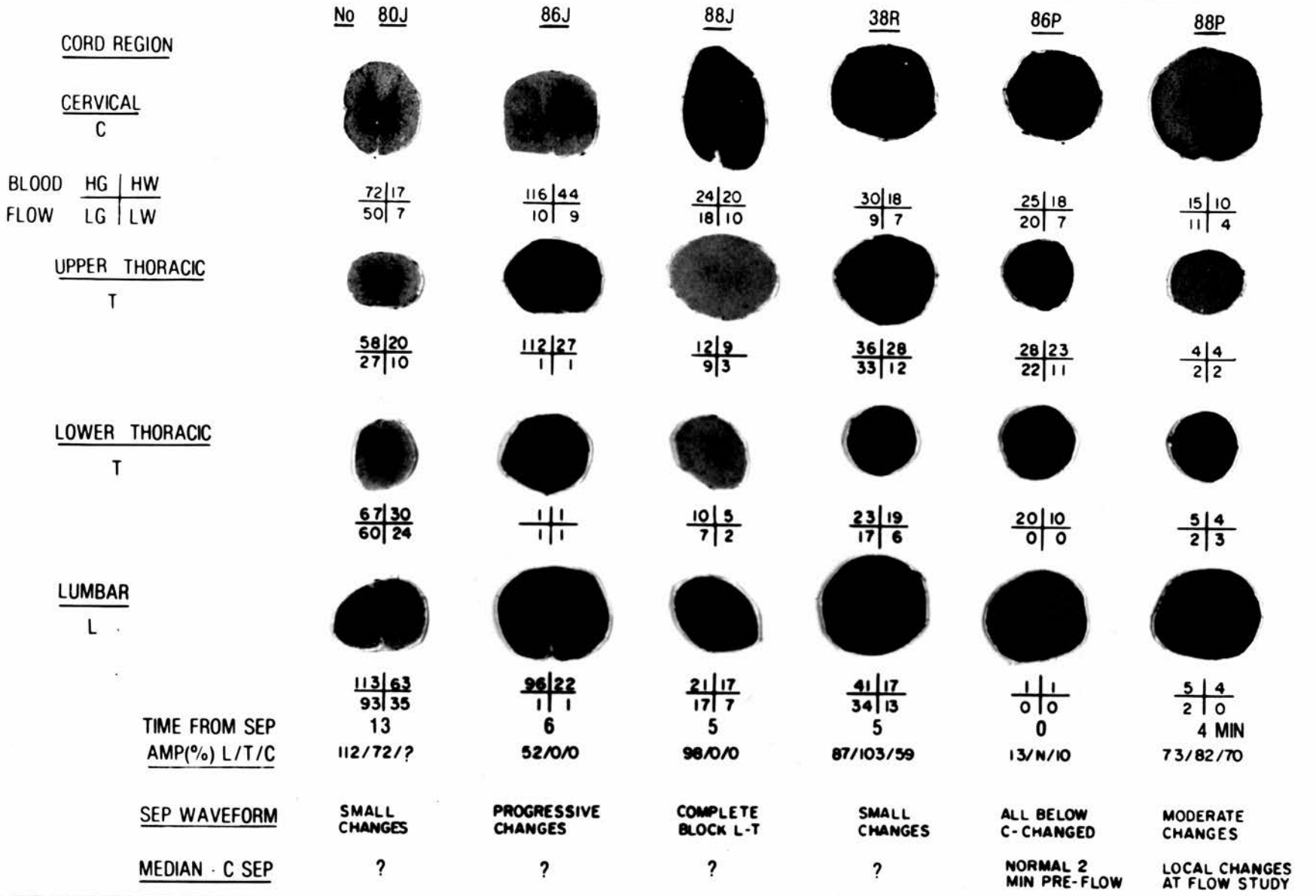
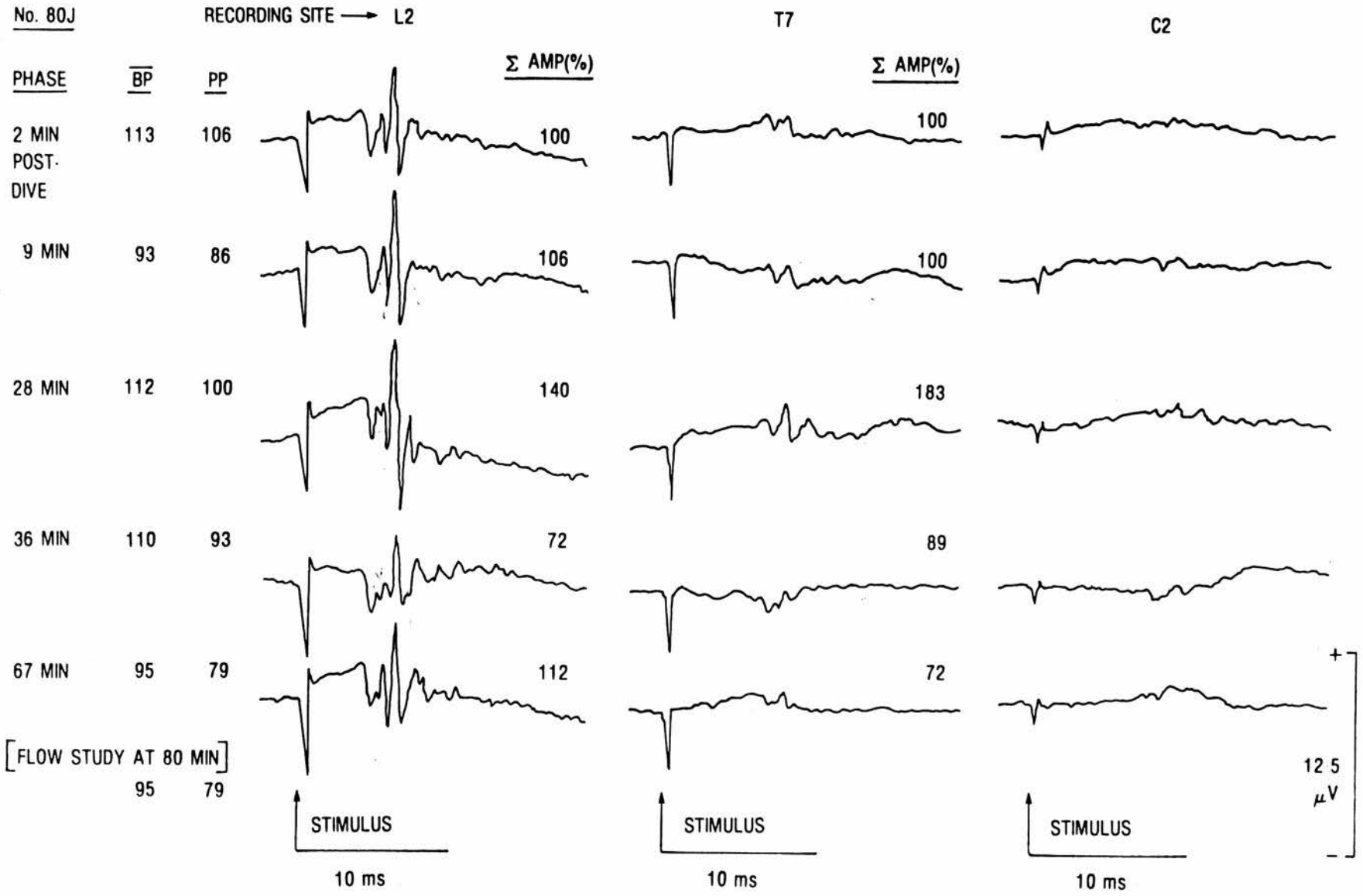


Figure 18. Right cortical mid-hemisphere coronal autoradiographs of 4 different dogs which experienced varying degrees of decompression sickness. 86J and 88J showed a frank change in EEG.


No 80J
86J
88J
38R
86P
88P
CORD REGION
CERVICAL
C
BLOOD FLOW
HG | HW
LG | LW
72|17
50|7
116|44
10|9
24|20
18|10
30|18
9|7
25|18
20|7
15|10
11|4
UPPER THORACIC
T
58|20
27|10
112|27
1|1
12|9
9|3
36|28
33|12
28|23
22|11
4|4
2|2
LOWER THORACIC
T
67|30
60|24
1|1
1|1
10|5
7|2
23|19
17|6
20|10
0|0
5|4
2|3
LUMBAR
L
113|63
93|35
96|22
1|1
21|17
17|7
41|17
34|13
1|1
0|0
5|4
2|0
TIME FROM SEP
13
6
5
5
0
4 MIN
AMP(%) L/T/C
112/72/?
52/0/0
98/0/0
87/103/59
13/N/10
73/82/70
SEP WAVEFORM
SMALL CHANGES
PROGRESSIVE CHANGES
COMPLETE BLOCK L-T
SMALL CHANGES
ALL BELOW C-CHANGED
MODERATE CHANGES
MEDIAN - C SEP
?
?
?
?
NORMAL 2 MIN PRE-FLOW
LOCAL CHANGES AT FLOW STUDY


No. 80J
RECORDING SITE → L2
T7
C2
PHASE
BP
PP
Σ AMP(%)
Σ AMP(%)
2 MIN POST-DIVE
113
106
100
100
9 MIN
93
86
106
100
28 MIN
112
100
140
183
36 MIN
110
93
72
89
67 MIN
95
79
112
72
[FLOW STUDY AT 80 MIN]
95
79
STIMULUS
10 ms
STIMULUS
10 ms
STIMULUS
10 ms
+
12 5 μV
−

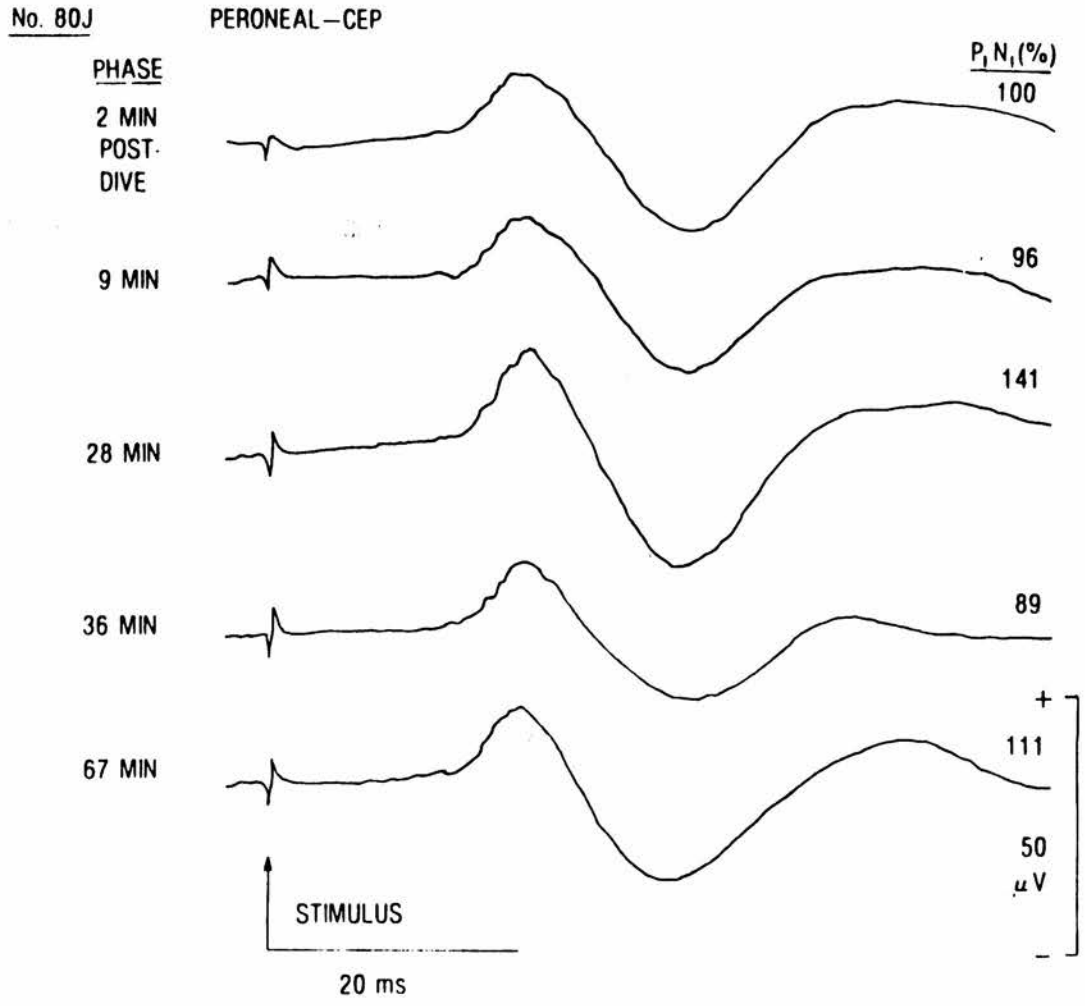


Figure 21. No 80J - Cortical evoked potentials from peroneal nerve stimulation. Time from surfacing is shown to the left and P_1N_1 amplitude as a percent of control to the right.

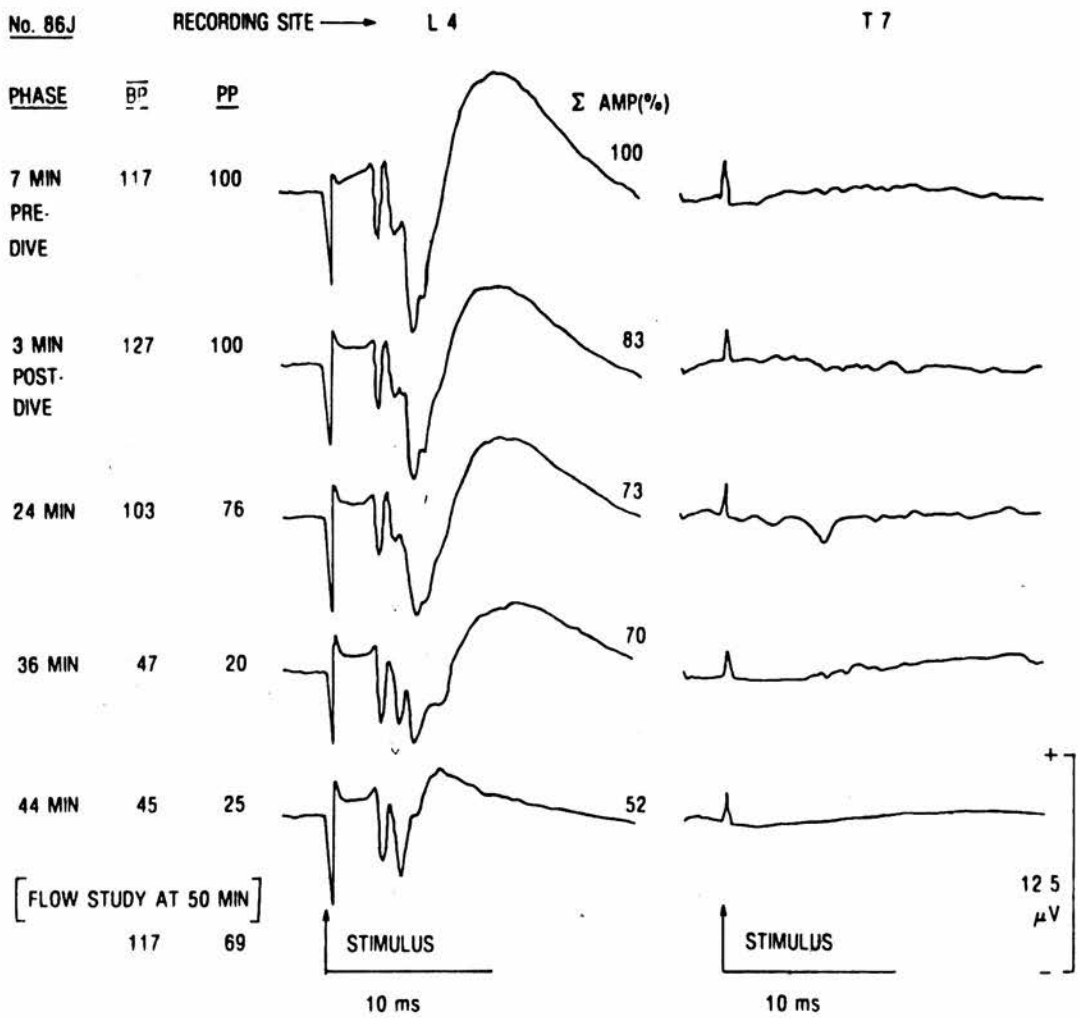


Figure 22. No 86J - Spinal evoked potentials from peroneal nerve.

was a sharp fall in BP at 37 min post-dive. Saline infusion and Levophed corrected this fall after 14 min. Local lumbar SEP changes were seen by 3 min (Figure 22). These progressed steadily until the last observation 6 min before the flow study. The peroneal-thoracic SEP disappeared between 36 and 44 min, indicating total conduction block in the upper lumbar-lower thoracic region. No median-cervical SEP changes were evident at 31 min. The flow study (Figure 19) at 50 min showed an almost complete absence of flow in the lower thoracic region, and gross asymmetry and heterogeneity in other segments. There were some areas of abnormally low flow in the cortex (Figure 18).

88J

After 5 min on the surface, CSFP began a small rise and EEG amplitude fell. By 13 min the EEG was almost isoelectric. Lumbar SEP remained unchanged throughout the observation period, but after 10 min no peroneal-thoracic SEP was visible. The flow study revealed a generalised reduction in blood flow, with very low flows evident in the whole of the thoracic cord (Figure 19). The cortical flow study showed marked flow deficits compatible with the EEG loss.

38R

Seven minutes post-dive there was a small rise in RVP and CSFP. EEG remained unchanged, but BP was elevated by about 50 mm Hg. At this point there were transient lumbar SEP changes. The median-cervical SEP was not observed within 10 min of the flow study. The flow study showed flows generally in the low end of the observed range, although none were in the neuron-disabling range (Figure 19). No abnormalities of cortical blood flow were seen.

86P (Figures 23 and 24)

There was a sharp rise in both RVP and CSFP after 2 min. They eventually rose by 52 and 34 mm Hg, respectively. There was a brief fall in BP to 70/50 mm Hg at 6 min. No change was seen in the EEG. Lumbar SEP changed at 6 min (Figure 23). The thoracic recording was destroyed by noise, not an uncommon finding in acute DCS. At the time of the flow study there was little left of the lumbar SEP and consequently nothing in the peroneal-cervical SEP. Two minutes before the flow study the median-cervical SEP was normal. The CEP reflected the loss of the peroneal-lumbar conduction (Figure 24), but

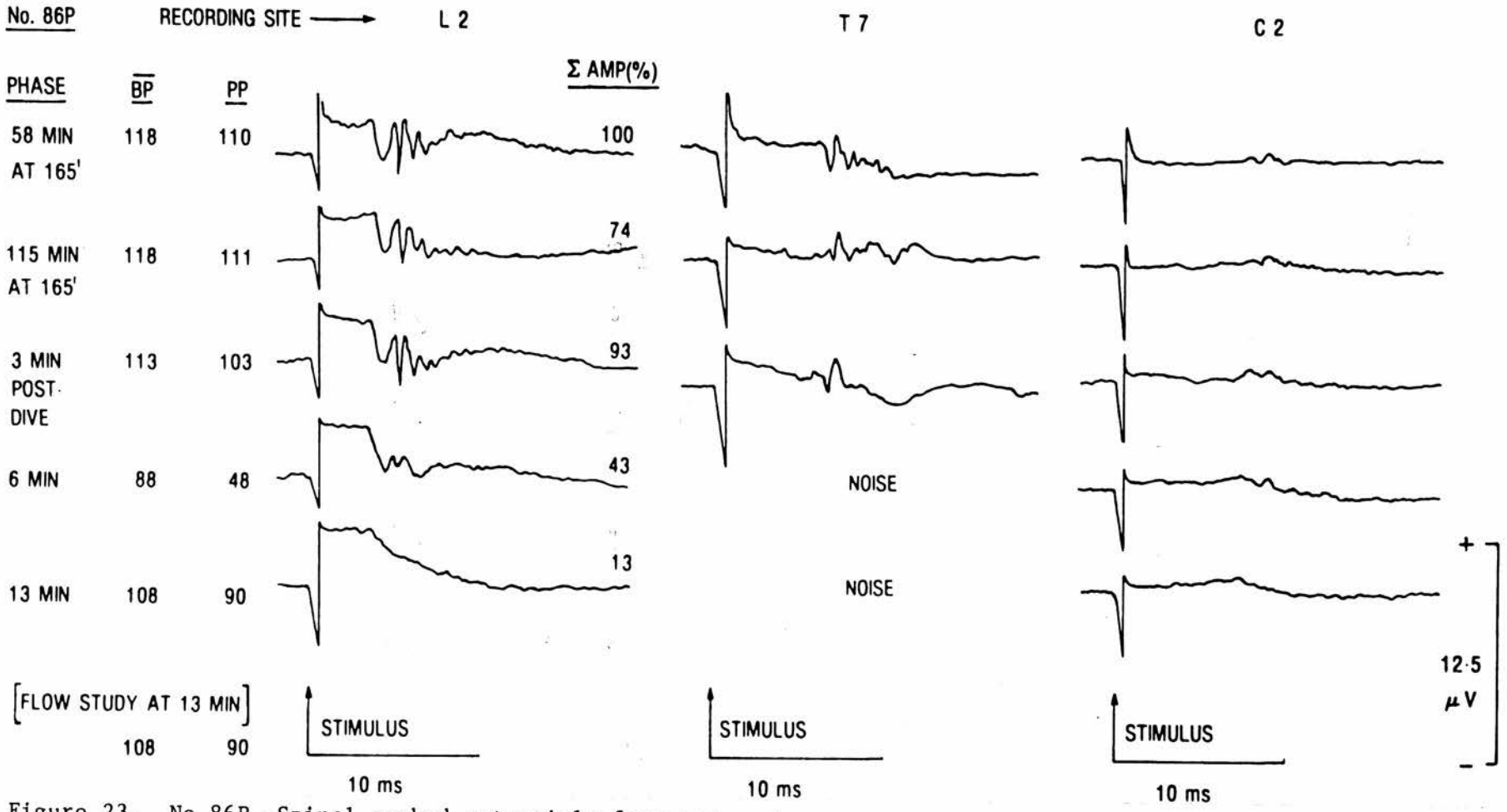


Figure 23. No 86P -Spinal evoked potentials from peroneal nerve.

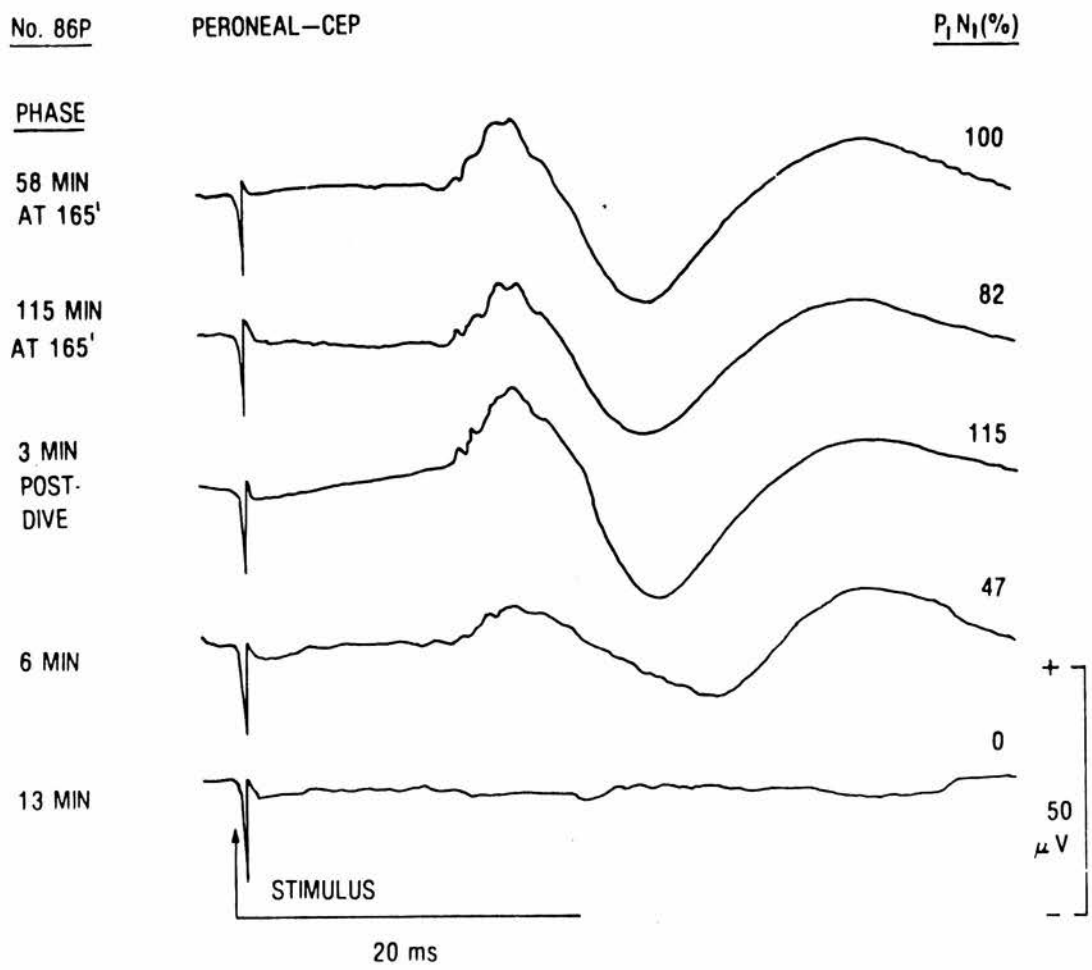


Figure 24. No 86P - Cortical evoked potentials from peroneal nerve.

the median CEP remained unchanged. The flow study showed a marked flow deficit in the distal half of the cord, while the rostral part appeared relatively normal (Figure 19).

88P (Figures 25 and 26)

Two minutes post-dive there was a generalised moderate increase in BP, RVP and CSFP. By 6 min, changes in the lumbar SEP were evident (Figure 25). Concurrently, the thoracic and cervical SEPs may have shown changes greater than those due to the lumbar changes alone. At 10 min there were local changes in the median-cervical SEP. The lumbar SEP changes were reflected in the CEP (Figure 26). The flow study done at 10 min showed a marked reduction in cord blood flow, particularly caudal to the cervical cord (Figure 19). There was some reduction in cortical flow in the inferior parts, remote from the subelectrode region (Figure 18).

7.4 DISCUSSION

The results from this study demonstrated that where there were clear SEP changes, there were also neuron-disabling low flows in the cord. Where there were transient SEP changes, the subsequent observation of hyperaemia suggested that these too might have been associated with transiently reduced blood flow. The appearance of patchy hyperaemia during recovery from gas embolism has been reported before (Hallenbeck et al., 1982; Leitch, et al., 1984). The observations of occasional spontaneous recovery conform with clinical experience. There was a good correlation between EEG changes and cortical blood flow. The two dogs showing EEG changes had flow deficits in the subelectrode regions. The approximate localisation provided by the EPs conformed to zones of impaired perfusion in cord and brain so that the electrical recordings were substantiated by the ^{14}C-iodoantipyrine autoradiographic flow studies.

An overall impression was that the degree and extent of neuron-disabling low blood flow was greater than the SEPs might have led one to expect. However, the intervals between the last peroneal SEP observations and the flow study ranged from 0 - 13 min, with a median of 5 min. It has already been shown that there is a lag time of about 4 min between cessation of blood flow and change in SEP travelling

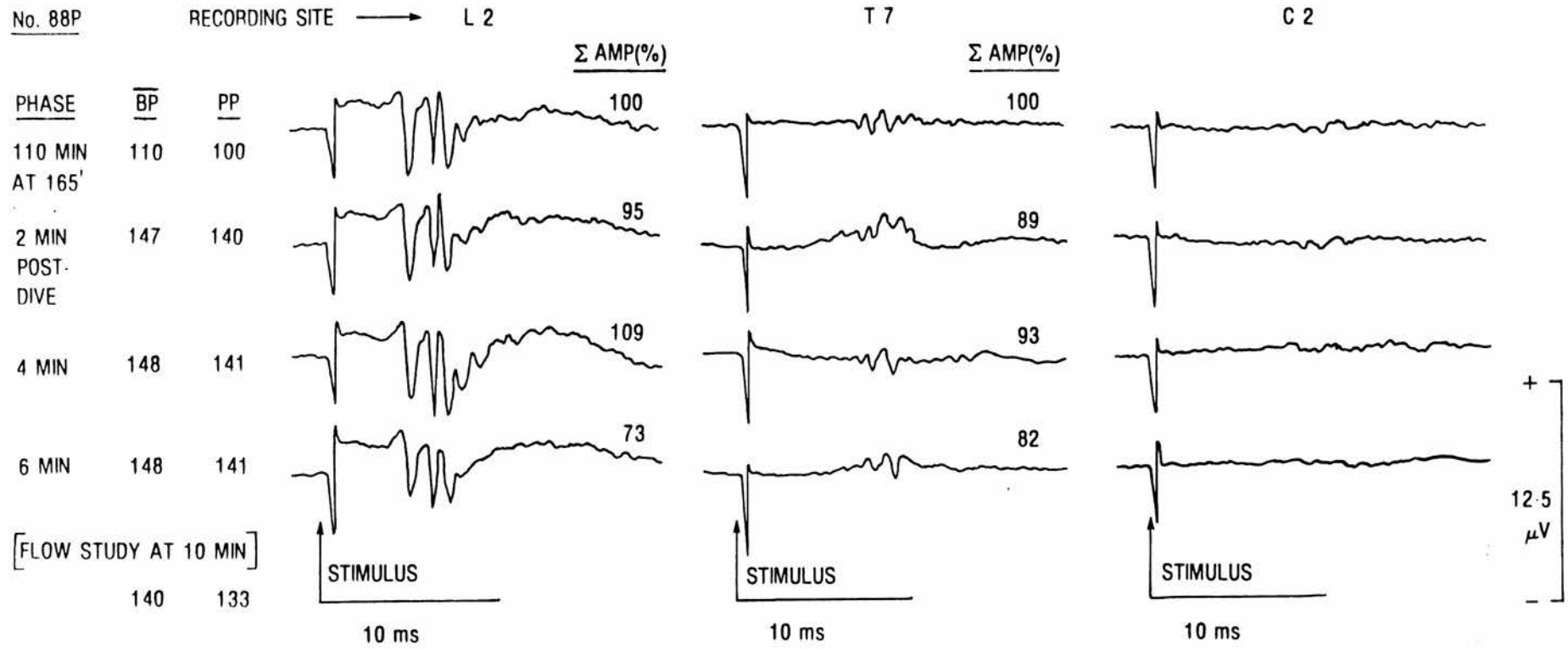


Figure 25. No 88P - Spinal evoked potentials from peroneal nerve.

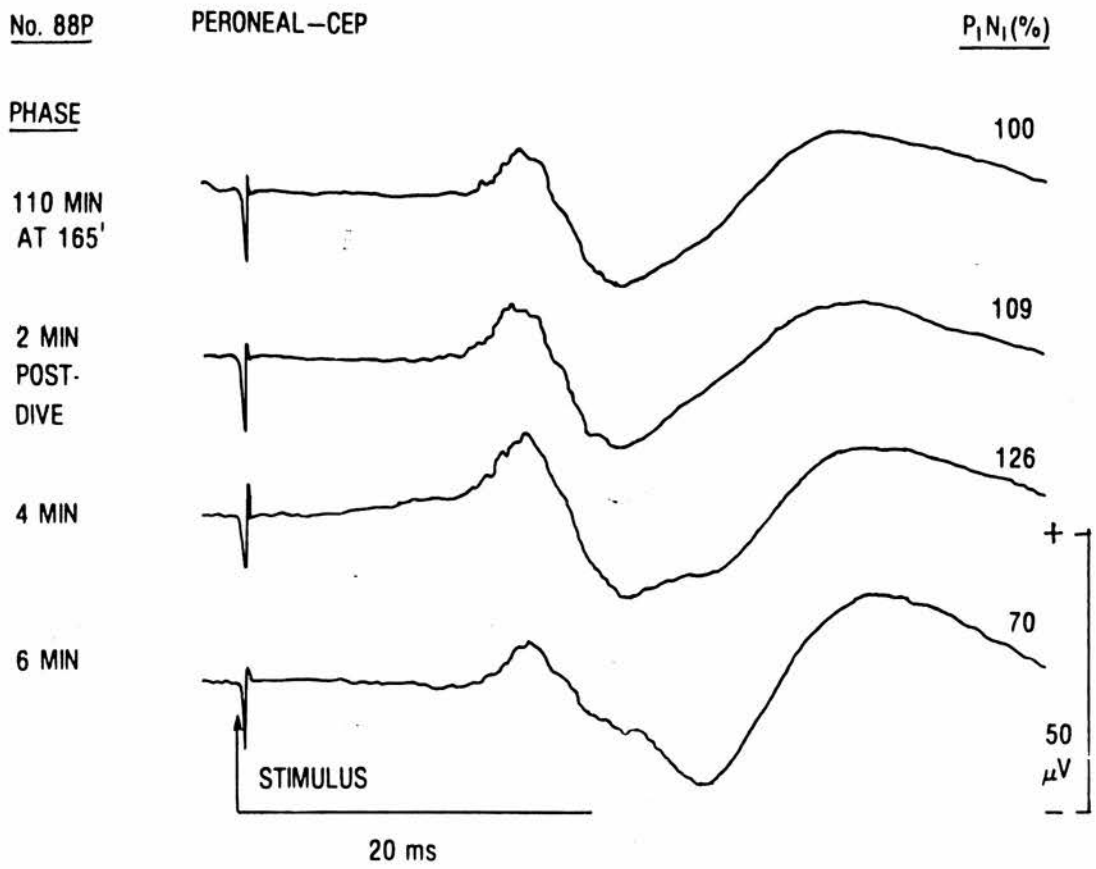


Figure 26. No 88P - Cortical evoked potentials from peroneal nerve.

waves. Similar observations have been made previously by others (Bernhard and Koll, 1953; Gelfan and Tarlov, 1955). Therefore, in a deteriorating situation, even when the flow study and last SEP observation are simultaneous, apparent function will probably be greater than the flow rate might predict. At no time were significant SEP changes seen that were not associated with a reduction in spinal cord blood flow to neuron-disabling levels. Therefore the validity of using evoked potentials to monitor spinal cord DCS was demonstrated.

SECTION 8

CONSISTENCY IN THE PRINCIPAL EXPERIMENTS

CONSISTENCY IN THE PRINCIPAL EXPERIMENTS

8.1 PREAMBLE

As the experiments were spread over a two year period, a check on the consistency of the electrophysiological model was maintained by comparing the effect of narcosis in each experiment. The principal experiments were the studies of oxygen and pressure as factors in treatment. The results from all other studies were incorporated into the first assessment of narcotic effect.

8.2 OXYGEN STUDY

The control data of the 25 dogs used in the oxygen study are given in Table 18 and 19. The amplitudes and latencies of the CEPs were as seen earlier. The same narcotic effect was also seen. The summated amplitudes for left and right peroneal to lumbar SEPs, and for median to cervical SEPs, were not affected by 10 bar of air being 98% (SE 2) and 99% (SE 2), and 99% (SE 1) respectively of controls.

Conduction velocities were calculated from interelectrode distances and peak latencies. The peroneal first travelling wave had a conduction velocity between stimulus and lumbar sites of 65 m^{-1} (SE 3). In the cord, velocity between lumbar-thoracic and thoracic-cervical sites was similar at 71 $m\,s^{-1}$ (SE 5) and 69 $m\,s^{-1}$ (SE 5) respectively. The median stimulus-cervical velocity was 79 $m\,s^{-1}$ (SE 4). The velocities from cervical site to cortex were 18 $m\,s^{-1}$ (SE 1) and 16 $m\,s^{-1}$ (SE 1). A later identified travelling wave had a much slower conduction velocity of 36 $m\,s^{-1}$ (SE 2) and 32 $m\,s^{-1}$ (SE 1) in the stimulus to first electrode segment for peroneal and median SEPs. In the peroneal SEPs this was reflected by a widening interval between the two waves as they passed rostrally. At the lumbar, thoracic and cervical sites the peak to peak intervals were 3.14 ms (SE 0.20), 3.86 ms (SE 0.22) and 4.38 ms (SE 0.26) respectively.

8.3 PRESSURE STUDY

Tables 18 and 19 show the control amplitude and latency data from the pressure study. The narcotic effect on CEPs at 10 bar was as previously seen. The SEP summated amplitudes were insignificantly

reduced by 10 bar of air, the left and right peroneal to lumbar, and the median to cervical SEPs being 97% (SE 2), 95% (SE 2) and 95% (SE 2) respectively of their controls.

In summary, CEP amplitudes were generally suppressed by 10 bar of air to about 80 percent of the control values. The latencies tended to be marginally increased but this finding was not consistent. The cord conduction velocities and CEP latencies were similar to those reported elsewhere (Norrsell, 1966; Parker 1978a; Parker, 1978b).

TABLE 18

CORTICAL EVOKED POTENTIAL AMPLITUDE.

Peak to Peak ($\mu V \bar{x} \pm SE$) (% of control)		P_1N_1	N_1P_2
Oxygen Study			
Peroneal	at 1 bar	33 ± 4	46 ± 6
	at 10 bar	81 ± 3%	81 ± 3%
Median	at 1 bar	48 ± 8	58 ± 9
	at 10 bar	75 ± 3%	81 ± 4%
Pressure Study			
Peroneal	at 1 bar	31 ± 5	43 ± 6
	at 10 bar	83 ± 3%	86 ± 3%
Median	at 1 bar	40 ± 5	50 ± 6
	at 10 bar	71 ± 2%	76 ± 2%

TABLE 19

CORTICAL EVOKED POTENTIAL LATENCY

Peak ($ms \bar{x} \pm SE$)		P_1	N_1	P_2
Oxygen Study				
Peroneal	at 1 bar	16.9 ± 0.4	25.0 ± 0.7	27.7 ± 1.0
	at 10 bar	17.2 ± 0.4	25.6 ± 0.7	38.2 ± 1.0
Median	at 1 bar	12.8 ± 0.2	19.5 ± 0.3	32.4 ± 0.8
	at 10 bar	12.9 ± 0.2	19.5 ± 0.4	32.8 ± 0.7
Pressure Study				
Peroneal	at 1 bar	15.8 ± 0.5	22.8 ± 0.5	34.2 ± 0.7
	at 10 bar	15.8 ± 0.5	23.1 ± 0.5	34.4 ± 1.0
Median	at 1 bar	12.8 ± 0.3	19.3 ± 0.4	31.9 ± 1.0
	at 10 bar	12.9 ± 0.3	19.3 ± 0.4	31.9 ± 0.8

SECTION 9

OXYGEN AND TREATMENT

OXYGEN AND TREATMENT

9.1 PREAMBLE

The objective of this study was to find the lowest effective PO_2 for the delayed treatment of spinal cord decompression sickness (DCS) at pressure. The lowest practical PO_2 was considered to be 1.0 bar and the highest to be 3.0 bar. To avoid the potential problem of giving dogs hypoxic mixtures, air with 20 - 21% oxygen was chosen as the lowest oxygen gas. This selected the pressure for all treatments as 5.0 bar, which with air gave a PO_2 of 1.0 bar. The pressure of 5.0 bar falls in the middle of the pressure range of treatments in common use.

9.2 METHOD

Dogs weighing between 9.1 and 13.6 kg were prepared as described before. However, the use of the intercostal stimulating site was abandonned because of the unreliability of the resultant SEPs. Dogs were assigned to one of the five treatment groups according to their weight. This ensured that the group mean weights were similar (range 11. 1 to 12.6 kg). All treatments were at a pressure of 5.0 bar (132 ft). Oxygen mixtures of 20, 30, 40, 50 and 60% in nitrogen were supplied to the ventilator. These gave a PO_2 of 1.0, 1.5, 2.0, 2.5 and 3.0 bar respectively at 5.0 bar. The experiments were cycled so that after each series of five treatments the next replication began one place to the right. The plan was to continue until it was clear that either there was no difference between treatments or that a statistically significant difference was sustained over two replications. In the event the difference was significant in the fourth and fifth replications. There are therefore five dogs in each group.

After satisfactory control measurements were made the chamber was compressed with air to a pressure of 10.0 bar (300 ft) at a rate of 75 ft min^{-1}. At pressure, duplicate EP recordings of the left peroneal and median nerve inputs were made. After a bottom time of 15 min (the first 4 dogs had shorter dives, 3 had 12 min and 1 did 14 min in a final adjustment to the dive) the chamber was decompressed

at a rate of 60 ft min^{-1} to 60 ft and at about 45 ft min^{-1} from 60 ft to the surface. This resulted in ascent times between 5.0 and 6.0 min. In practice the chamber was held with 1 to 2 ft of pressure at the surface in order to make the ventilator oxygen dump bag vent from the chamber.

Continuous EP recordings were made after arrival at the surface. Left and right peroneal recordings were alternated on a 3 to 4 min cycle. This allowed observation of the whole length of the cord. As soon as a minor change was observed which was seen to progress on the next recording, the diagnosis of DCS was made. Compression for treatment began 14 to 17 min after the diagnosis was made. If a lesion was identified in the cervical region during a peroneal recording the next interrogation would be the median. The SEP for the affected region was used for the control and assessment of the subsequent experiment.

If after a 30 to 40 min surface interval no SEP changes were seen the dog was given another dive with a bottom time of 9 to 13 min. This was necessary in seven of the 25 dogs. When any dog with DCS developed hypotension during the surface interval this was corrected with lactated Ringers solution. Additional fluid was given to correct the haemoconcentration commonly seen. Hypotension and haemoconcentration were usually associated with an acidosis which was corrected with 8% sodium bicarbonate. Fluid balance was recorded over the period beginning with the dive until the end of treatment.

There were six criteria used to eliminate dogs from the study group. the criteria were:

a. A missed diagnosis resulting in the pre-treatment interval being too long.
b. Insufficient loss of SEP amplitude (< 10% loss).
c. Hypotension resulting in systolic blood pressure being below 100 mm Hg for more than 5 min.
d. Failure to show more than 5% recovery at any stage in the treatment.
e. Any degree of spontaneous recovery during the pre-treatment interval.

f. Sudden cardiovascular collapse during treatment.

Immediately before compression for treatment a last record of the controlling SEP was made. The correct gas was switched to the ventilator and the chamber compressed to 5.0 bar at 75 ft min^{-1}. The treatment gas was breathed without break thereafter. A repeat of the controlling SEP plus the remainder was made on arrival at pressure. The SEP recordings were repeated at 15 min. Thereafter all SEPs demonstrating lesions were checked every 15 min and the rest at 30 min until 120 min of treatment were completed.

The final pretreatment SEP was expressed as the percent of control which was lost. If there was a further loss of SEP amplitude during compression the lower value was taken as the loss. All recovery was then expressed as a percent of what was lost as a normalising procedure. The reported treatment data were reduced to the nearest recording to the 15, 40, 80 and 120 min points. All results are expressed as the mean ± one standard error. The basic statistical analysis was a one way analysis of variance.

After the experiments were terminated the spinal cords were removed from 11 dogs and fixed in phosphate-buffered 10 percent formalin (4% W/V formaldehyde). These were sectioned and stained with haemotoxylin and eosin for light microscopy. The cord was cut into seven gross segments and three or more specimen sections from each segment were observed for frequency of haemorrhage. The objective was to see whether there was any correspondence between SEP recovery and the frequency of haemorrhage in the cord.

9.3 SYSTEMIC CHANGES

The earliest change indicating DCS in this model was a reduction in EEG amplitude. The reduction ranged from about 15 percent to the EEG being isoelectric. Eighty percent of dogs were affected (Table 20). This occurred 1 to 16 min after surfacing. Cerebrospinal fluid pressure rose in most dogs to levels shown in Table 21. The rise in CSFP began from 1 to 16 min after surfacing. These times were not coincident with the EEG changes. However the two dogs which

did not show a rise in CSFP did not experience a reduction in EEG amplitude. Fifteen dogs experienced a rise in RVP to as high as 120/20 mm Hg (Table 21). In 8 this rise occurred later than the CSFP rise. Towards the end of the pretreatment period, the raised RVP began to fall in 20 dogs and the raised CSFP began to fall in 15 dogs. In the remainder it remained constant or rose further. compression therapy caused random changes in CSFP but generally caused RVP to stabilise at around control levels (Table 21).

During the pretreatment interval 9 dogs had an increase in systolic blood pressure of more than 20 mm Hg above any pre-diagnosis pressure (Tables 20 and 21). In three cases this exceeded 300 mm Hg. In most cases of hypertension there was a precipitate fall in pressure within a few minutes. When pressure rose rapidly and levelled off, infusion of lactated Ringers solution was started to prevent the rebound hypotension where systolic blood pressure fell below 100 mm Hg. Of the five dogs in the final data pool which were transiently (< 5 min) hypotensive only three had been hypertensive. Cerebral perfusion pressure calculated as the difference between CSFP and mean blood pressure is shown in Table 21. Heart rate generally increased at some stage before treatment then returned to pre-DCS levels. Ventilation rate was controlled completely in most dogs. During the DCS there were occasional episodes of tachypnea attributable to "chokes".

TABLE 20

EVENT TIMES DURING DECOMPRESSION SICKNESS

PO_2 (Bar)	1.0	1.5	2.0	2.5	3.0	F-ratio
EVENT						
Surfacing to D	12 ±3	15 ±3	19 ±2	17 ±3	12 ±3	1.24
D-1 to D	4 ±1	5 ±1	5 ±1	8 ±3	5 ±1	0.80
Last SEP to TR	2 ±2	1 ±1	2 ±1	3 ±1	3 ±2	0.53
RVP ↑	(5)9	(4)9	(3)12	(2)5	(3)5	-
CSFP ↑	(5)4	(5)6	(4)8	(4)5	(5)4	-
EEG ↓	(4)2	(4)3	(3)11	(3)4	(4)5	-
BP ↑	(2)11	(4)14	(0)-	(1)13	(2)14	-
BP ↓	(0)-	(2)18	(0)-	(1)6	(2)10	-

Times in minutes shown as mean ± 1 standard error. Figures in parenthesis indicate numbers of dogs. D - diagnosis of DCS in the SEP, D-1 - last normal SEP, TR - start of treatment.

In spite of the volumes of fluid given before treatment began, only 10 dogs had an increase in haematocrit of 3 percent or less (Table 22). The greatest increase seen was 16 percent. Overall the increase was significant ($P < 0.05$) for both the increase and the absolute level. The group mean increases were 6, 12, 8, 3 and 4 percent respectively. The urine outputs in Table 22 were from the start of the dive until the end of treatment, a period of about 3 hours.

A marked respiratory acidaemia occurred during the pretreatment phase (Table 23). Nine dogs had an arterial pH of less than 7.3 which was caused by an elevation in arterial PCO_2. In 12 dogs $PaCO_2$ exceeded 39 mm Hg and in four of these $PaCO_2$ exceeded 45 mm Hg. There was no independent change in bicarbonate ion concentration coincident with this. There was however a slight hypoxaemia when 12 dogs had an arterial PO_2 of less than 85 mm Hg. This resolved on compression treatment with high oxygen mixtures.

TABLE 21

CARDIOVASCULAR VARIABLES

PO_2 (bar)	1.0	1.5	2.0	2.5	3.0	F-ratio
MEAN BLOOD PRESURE (mm Hg)						
Post-dive	114±4	116±6	126±5	108±4	114±9	1.08
Interval range	77-220	70-257	87-150	70-152	70-147	-
Pre-treatment	89±3	103±14	112±8	100±9	92±8	1.02
Change on						
Compression	-26(5)	-18(4)	-12(4)	-17(5)	-12(4)	0.49
Tr 15 min	127±11	137±24	116±10	113±4	125±9	0.53
Tr 120 min	110±16	108±9	118±3	105±10	120±113	0.34
RIGHT VENTRICULAR PRESSURE (mm Hg)						
Post-dive	18/1	25/0	18/1	25/5	20/0	1.73
Interval range (Syst)	6-120	20-105	14-60	18-85	16-60	-
Pre-treatment	33/7	40/4	29/1	31/6	27/0	0.92
Tr 15 min	21/3	34/1	21/1	27/5	30/1	3.23*
Tr 120 min	16/0	20/0	16/1	23/4	21/1	0.93
CEREBROSPINAL FLUID PRESSURE(mm Hg)						
Post-dive	11±2	10±3	5±1	16±6	13±3	1.07
Interval range	5-36	1-82	2-28	2-38	4-32	-
Pre-treatment	18±3	23±8	12±4	13±4	18±5	0.68
Tr 15 min	27±8	20±5	9±3	21±4	24±6	1.15
Tr 120 min	19±8	21±8	6±3	22±6	18±3	1.21
CEREBRAL PERFUSIONS PRESSURE (mm Hg)						
Post-dive	104±5	106±7	120±5	92±7	101±8	2.32
Pre-treatment	71±4	79±12	100±7	87±9	74±9	2.12
Tr 15 min	101±8	117±22	108±8	92±7	102±10	0.55
Tr 120 min	92±16	87±10	115±8	83±13	102±13	1.01

Pressures in mm Hg shown as mean ± 1 standard error. Mean blood pressure = diastolic BP + 2/3 pulse pressure. Figures in parentheses indicate numbers of dogs. *Under F-ratio column shows significance at $P < 0.05$.

It can be seen that except for CSFP all the pressures stabilised at a level a little below control values, during treatment. The haematocrit, arterial pH and PCO_2 all returned to levels not greatly different from the controls. There were only two instances where the groups were statistically different: the pretreatment haematocrit and the RVP after 40 min of treatment ($P < 0.05$). Compression caused an at least transient drop in mean blood pressure. The two dogs which showed a rise in pressure were both hypotensive at the start of compression (Table 21).

TABLE 22

HAEMATOCRIT AND FLUID BALANCE

PO_2 (bar)	1.0	1.5	2.0	2.5	3.0	F-ratio
Hct Control (%)	46 ±1	45 ±1	43 ±2	46 ±1	45 ±1	0.98
Pre-Treatment	52 ±3	57 ±3	48 ±2	46 ±1	49 ±2	3.81*
Tr 40 min	51 ±2	47 ±3	44 ±1	44 ±1	48 ±2	2.76
Tr 80 min	50 ±1	46 ±2	44 ±1	45 ±3	48 ±2	1.85
Overall Fluid Balance (ml)	261 ±48	204 ±8	94 ±56	155 ±64	216 ±78	0.92
Fluid-in in Tr (ml)	230 ±89	252 ±79	196 ±38	109 ±23	194 ±47	0.57
Urine output (ml)	126 ±22	195 ±60	170 ±31	103 ±18	144 ±22	1.11

Data given as mean ± 1 standard error. Tr- treatment.* under F-ratio indicates a significance of $P < 0.05$.

TABLE 23

ACID-BASE AND GAS ANALYSIS

PO_2 (Bar)	1.0	1.5	2.0	2.5	3.0	F-ratio
ARTERIAL pH						
Control	7.39±0.02	7.39±0.02	7.38±0.02	7.41±0.02	7.39±0.02	0.56
Pre-Tr	7.31±0.04	7.31±0.01	7.34±0.02	7.31±0.03	7.32±0.03	0.29
Tr 40 min	7.35±0.01	7.39±0.03	7.38±0.02	7.38±0.01	7.38±0.02	0.25
Tr 80 min	7.39±0.02	7.39±0.02	7.36±0.01	7.39±0.02	7.39±0.03	0.38
ARTERIAL PCO_2 (mm Hg)						
Control	34±2	34±2	35±2	32±1	34±1	0.55
Pre-Tr	42±5	38±1	40±3	39±3	40±3	0.22
Tr 40 min	35±1	35±2	37±6	36±3	34±2	0.07
Tr 80 min	38±2	38±4	39±3	34±2	36±4	0.33
END TIDAL PCO_2 (Percent)						
Control	3.9±0.2	3.7±0.1	4.0±0.1	3.6±0.2	4.1±0.1	1.81
Pre-Tr range	2.6-4.7	2.6-5.0	3.2-4.9	2.9-4.4	2.5-5.2	-
Pre-Tr	2.8±0.2	4.0±0.3	4.1±0.3	3.9±0.3	4.1±0.3	0.32
Tr 40 min	4.7±0.3	4.6±0.3	4.5±0.4	4.4±0.3	4.4±0.2	0.18
Tr 80 min	4.4±0.5	4.6±0.2	4.5±0.1	4.2±0.4	4.5±0.3	0.27
ARTERIAL PO_2 (mm Hg)						
Control	94±2	92±3	92±1	95±3	94±2	0.27
Pre-Tr	80±11	80±6	90±5	94±6	89±6	0.71

Data shown as mean ± 1 standard error. Tr - treatment.

9.4 SPINAL EVOKED POTENTIALS

Examples of SEP changes during two experiments are shown in Figures 27 and 28. The first identified SEP lesions in the 25 dogs in the final data pool included, 16 left lumbar, 6 right lumbar, 1 right thoracic and 2 left cervical lesions (Table 26). These SEPs were used for diagnosis and assessment of recovery. The loss of SEP amplitude ranged between 15 and 100 percent by the start of treatment. At the start of treatment there was no significant difference in severity between the groups (Table 24 and 26).

The time from surfacing at which SEP change was identified ranged between 4 and 25 min. There was no difference between the group means (Table 20). The extent of the change leading to diagnosis

(D-1 to D) ranged between 2 and 60 percent (Table 24). With the exception of one dog in the 2.5 bar group which had a 20 min interval between the last normal and diagnostic SEPs, most intervals were 4 to 5 min (Table 20). Inspite of the long interval in that case the SEP loss at diagnosis was only 4 percent. As a check on diagnostic perception the penultimate normal SEP (D-2) was checked against the last presumed normal SEP (D-1) and no difference between the groups was seen (Table 24), nor was any large change found. Where the time to onset was short there were 9 cases where D-2 was measured at pressure in the dive.

TABLE 24

CHANGES IN SPINAL EVOKED POTENTIALS

PO_2 (bar)	1.0	1.5	2.0	2.5	3.0	F-ratio
TIME PERIOD						
D-2 to D-1	-1 ±2	-1 ±3	+3 ±5	-1 ±2	-2 ±4	0.94
D1 - D	-24 ±5	-11 ±4	-25 ±11	-25 ±11	-21 ±2	0.59
D to Pre-Tr	-44 ±13	-28 ±8	-47 ±12	-41 ±15	-49 ±9	0.52
Pre-Tr loss	67 ±11	52 ±13	69 ±9	68 ±16	65 ±11	0.52

Change in SEP as a percent of control shown as mean ± 1 standard error. D-2 - penultimate normal SEP, D-1 - last normal SEP, D - diagnostic SEP, Tr - treatment.

The progression of the SEP amplitude loss between diagnosis and start of treatment (D to Pre Tr) is shown in Table 24. The cord lesions were not stable at the start of treatment. All SEPs were continuing to deteriorate at varying rates. The interval between the last pre-treatment SEP and the start of compression therapy varied between 0 and 8 min (Table 20). Two dogs showed a further loss of SEP during compression. One lost another 31 percent and the other 8 percent. They respectively had a 0 and 7 min interval between the last SEP and the start of treatment.

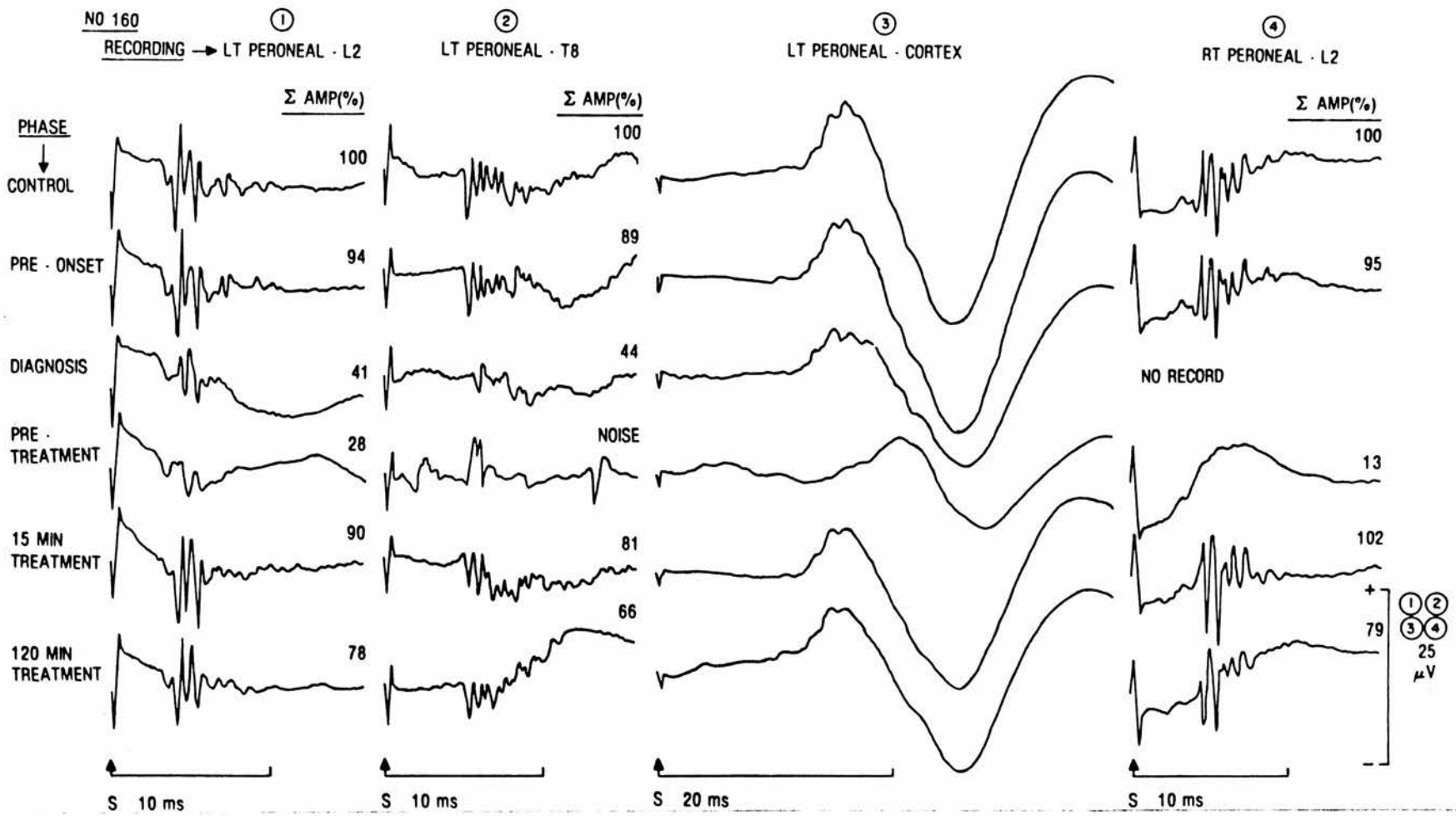


Figure 27. No 160 - Spinal and cortical evoked potentials. The experiment was controlled around the left lumbar SEP (1). The development of DCS and its recovery through treatment is shown. The summated amplitude as a percent of control is given under Σ Amp (%). The effect of the left lumbar lesion on the thoracic SEP and cortical evoked potential is also shown. There was also DCS in the right lumbar cord.

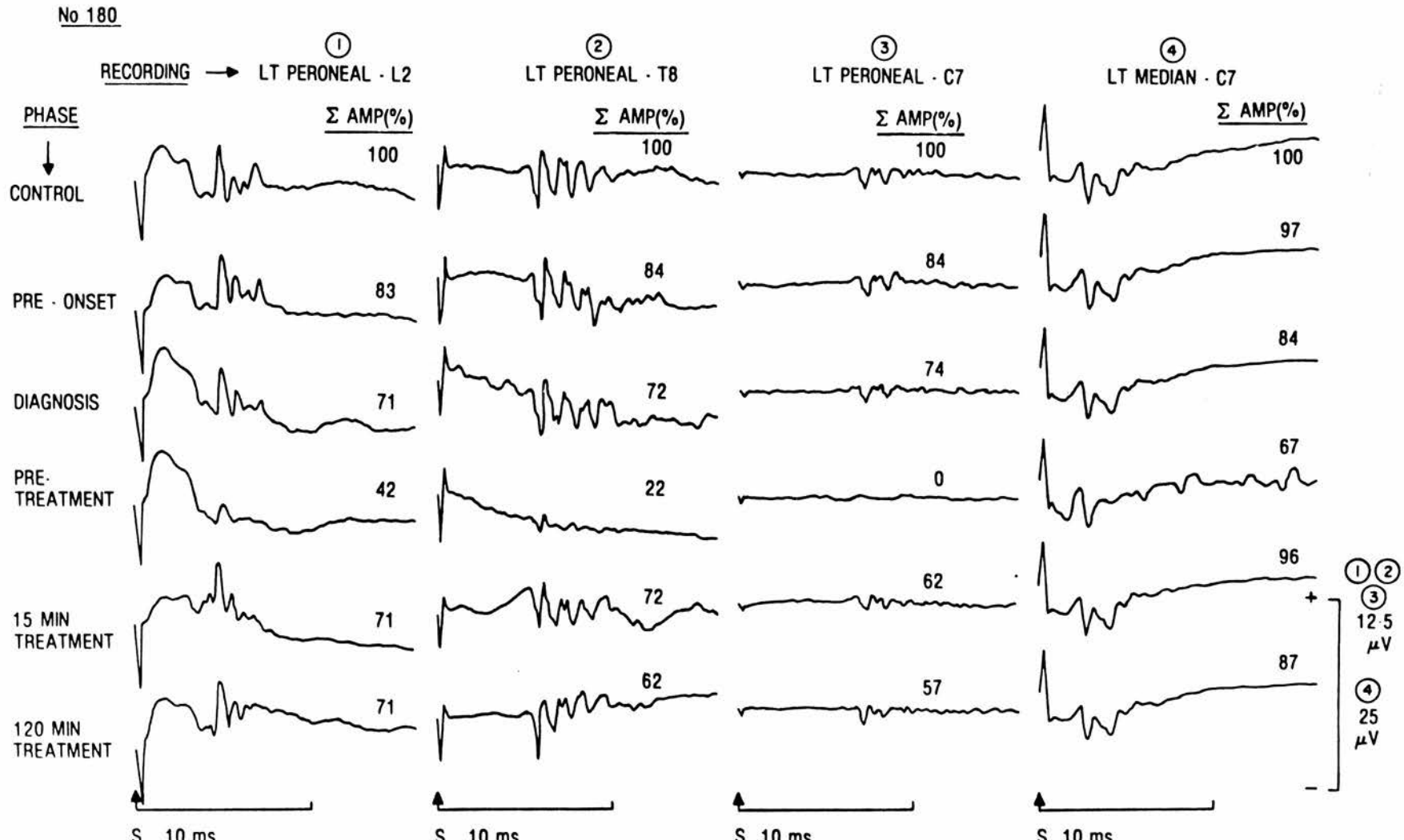


Figure 28. No. 180 - Spinal evoked potentials. The experiment was controlled around the left lumbar SEP. The effect of the lumbar lesion can be seen in the thoracic and cervical SEPs. In addition there was DCS in the cervical cord.

Recovery of SEP amplitude was rapid in the first 15 min of treatment (Table 25) and ranged between 5 and 100 percent. Although the 2.0 bar group led the recovery at 15 min there was no significant difference between groups. In the three groups with a PO_2 of 2.0 bar or more, mean group recovery continued out to 40 min. In the two lower PO_2 groups, deterioration occurred between 15 and 40 min (7/10 cases) and the SEP amplitude stabilised for the remainder of the 2 hours of treatment. The differences between the groups at 40, 80 and 120 min were significant ($P < 0.05$) with the 2.0 and 2.5 bar oxygen treatment groups having the same mean recovery at 70 and 66 percent. Two dogs, one in each of the 1.0 and 1.5 bar groups ended with no recovery, in fact with even a further SEP loss, having shown 74 and 53 percent recovery at 15 min. The peak recovery times covered the entire treatment period. Using all the available SEP data showed the group mean peak recovery times to be 60, 32, 54, 65 and 58 mins (F ratio 0.44). the mean SEP recovery at these times was 63, 79, 91, 80 and 58 percent (SE 6 to 13, and F ratio 1.43).

The extent of CNS involvement as far as it was possible to assess it is shown in Table 26. This includes the onset times for EEG changes as well as the pretreatment SEP amplitude loss. As travelling waves are recorded more rostrally the reducing amplitude must lead to a greater error and therefore possible inconsistency in SEP loss.

TABLE 25

SEP RECOVERY AS PERCENT OF LOSS

PO_2 (bar)	1.0	1.5	2.0	2.5	3.0	F-ratio
TIME PERIOD						
at 15 min	42 ±13	55 ±15	70 ±11	52 ±11	44 ±11	0.84
at 40 min	29 ±10	33 ±10	79 ±9	69 ±12	53 ±13	3.92*
at 80 min	29 ±14	30 ±11	68 ±6	71 ±11	39 ±8	3.79*
at 120 min	22 ±10	34 ±10	70 ±12	66 ±14	42 ±8	3.53*

Recovery of SEP during treatment expressed as percent of loss shown as mean ± 1 standard error. * Under F-ratio column shows significance at $P < 0.05$.

However some local activity is included in the peroneal-lumbar SEPs so it would be possible to see the local loss without affecting the travelling waves rostrally as possibly shown in dog 174. If the lumbar SEP loss is total then no assessment of thoracic cord can be made. Expressing the number of affected SEPs as a percent of available recordings showed the proportion of affected cord segments in each group to be about 55, 59, 56, 39 and 67 percent respectively. Taking only the left and right lumbar and the left cervical segments, those with large reliable SEPs, the figures were 87, 80, 71 53 and 60 percent respectively. There was no consistent pattern of involvement related to recovery.

9.5 DISCARDED DATA

Eight dogs were lost for various technical reasons. Another four completed treatment without any recovery of SEP at any time. Of these, two had a missed diagnosis which led to a pretreatment phase of more than 35 min. One experienced 9 min of profound hypotension (Systolic BP 70 mmHg). The other developed an uncontrollable respiratory and acid-base problem which resulted in 80 min with a pH between 7.20 and 7.29 and a $PaCO_2$ of 80 mm Hg. These dogs were replaced in the data pool.

9.6 PATHOLOGY

A few petechial subarachnoid haemorrhages were seen in some dogs when the cords were removed. A major subarachnoid haemorrhage was present in the lumbar-thoracic cord of dog No. 184. There was poor SEP recovery in this case with a slow improvement reaching 12 percent at 120 min.

Many cord segments showed varying degrees of haemorrhage and occasional vascular congestion. There were microscopic petechiae in either or both of the grey and white matter. Most appeared in the central grey matter. The haemorrhages consisted of small clusters of red cells surrounding capillaries and venules to larger though still microscopic foci of bleeding. The appearance was compatible with hypoxia or embolic episodes. There was no other evident tissue

damage, inflammatory infiltration or oedema. There was no detectable relationship between frequency of severity of haemorrhage and extent of SEP loss, its recovery, or subsequent deterioration. However the one case (No. 174) with the least SEP loss and the least cord involvement (left lumbar only) also had the smallest number of haemorrhages.

TABLE 26

EXTENT AND SEVERITY OF CNS DECOMPRESSION SICKNESS

EVOKED POTENTIAL	LPL	LPT	LPC	RPL	RPT	RPC	LMC	EEG (Time)
DOG								
140	[79]	?	86*	82*	?	100*	11	-
141	[28]*	?*	54*	11*	?*	33*	48*	1
142	[92]	100	100	90	100*	100*	65	4
143	[75]	100	100	20*	25	55	0	1
144	19	23	49	[62]	22*	37*	0	3
150	[18]	?*	?	14	?	100	0	-
151	[61]	47	57	47*	?	40*	0	3
152	17*	?*	0*	[29]*	26*	27	0	4
153	62	100	100	59	100	100	[89]	1
154	8*	?*	32*	41*	41*	100	[63]	6
160	[72]	56	?	86	?	?	0	-
161	59	?	?	[71]	?	?	?	-
162	0	0	0	[49]	31	48	0	16
163	[100]	?	?	100	?	?	0	7
164	[54]	100	100	66	100	100	58	11
170	?	38	64	11	[83]	100	27	3
171	[100]	100	100	100	100	?	0	-
172	[91]	80	100	81	100	100	0	6
173	[53]	36	?	0	0	?	0	-
174	[15]	0	?	0	?	?	0	2
180	[58]	78	100	0	0	0	33	1
181	68	70	100	[77]	64	?	0	-
182	[44]	28*	43	0	23	30	0	13
183	[100]	100	100	84	77	53	0	3
184	86	100*	100*+	[97]	?*	100*+	0+	3

Data are presented as percent of control SEP lost at the start of treatment. [ ]-principal and controlling SEP, ? - no record, * - no recovery at 120 min, + - cord haemorrhage at post mortem. Evoked potentials are LPL - left peroneal lumbar, thoracic and cervical, RPL - right peroneal lumbar, thoracic and cervical, LMC - left median cervical. Figures in EEG column are onset times in minutes.

9.7 DISCUSSION

At the start of treatment the physiological condition of the five groups of dogs was similar except for the mean haematocrit in the 1.5 bar group which was higher than the rest. All groups had cord DCS of similar severity and similar development. During treatment a large proportion of the mean SEP recovery had occurred in all groups by 15 min. This was not sustained in the 1.0 and 1.5 bar groups. The higher PO_2 groups recovered further by 40 min before stabilising at a lower level between 40 and 120 min. Throughout the later part of treatment there was a significant difference between the groups with the 2.0 and 2.5 bar groups showing the best mean recovery of 70 and 66 percent respectively.

The choice of 15 min for the interval between diagnosis and the start of treatment seems to have been correct. Only four dogs achieved a complete recovery but two of these failed to sustain it. The preliminary studies showed that complete recovery was unlikely after total ischaemia lasting 15 min. There was a risk, if additional pressure was more effective than oxygen in treating DCS, that 5.0 bar could mask any oxygen effect. This did not occur.

There was a strong indication of peripheral vascular obstruction by gas in that 22 dogs (88%) showed a transient step reduction in mean blood pressure during the compression phase of treatment. Compression of intra- or extravascular obstructing gas would lead to a sudden drop in peripheral resistance and a transient fall in blood pressure. There was no apparent reason why the SEPs of 2 dogs should have deteriorated transiently on compression. The finding is similar to occasional clinical experience. It might result from vessel collapse on compressed bubbles or gas redistribution transiently worsening a local problem. There was no association with higher oxygen which would implicate oxygen uptake in the bubbles. If the efficacy of specific treatments and speed of treatment are disregarded there are two major factors which may govern the extent of recovery; first the severity and extent of cord involvement, and secondly aspects of systemic disturbance which will influence microcirculatory perfusion, such as perfusion pressure, haematocrit and acid-base state.

When monitoring function using EPs it is possible to obtain a crude estimate of the extent of cord involvement by differentiating between left and right and by having several interrogation points. There were five cases of unilateral lumbar SEP loss. The median-cervical SEP showed the left cervical cord to be unaffected in 16 cases where the lumbar cord was affected. Separating the cases into those showing generalised cord involvement and those only 'locally' affected gave respective mean recoveries at 120 min of 41 and 50 percent ('t' test $0.1 > p > 0.05$). This could have influenced the treatment group means as only 3 of the 8 cases affecting cervical cord occurred in the three high oxygen groups (Table 26). There was a smaller difference when unilaterally and bilaterally affected lumbar SEPs were compared ($p < 0.6$). Within the treatment group means there was no difference between the losses in the primary SEPs. When all the primary SEP losses were divided between generalised and local cord DCS the SEP losses were the same with 68 and 65 percent respectively. So severity of SEP loss does not seem to be related to extent of cord involvement but greater extent may reduce recovery.

Although there was no significant difference in mean onset times between groups, the two best groups had longer onset times than the remainder. There was no relationship between onset time of SEP loss and the amount lost. However, there was a relationship between onset time and amount of recovery. The least squares regression equation was:

$$Y = 12.92 + 2.18t$$

where Y was the percent recovered and t the onset time in minutes ($R = 0.48$, $p < 0.02$). Separating recovery into those with less than 40 percent and those with more than 60 percent gave mean onset times of 13.5 and 19.0 min ('t' test $p < 0.001$). Thus speed of onset may indicate a poorer chance of recovery. There was no difference between these two groupings for percent of SEP loss, 59 and 62 percent respectively so recovery was not related to severity.

There was an indication of brainstem involvement in possibly nine cases. Such lesions could arise from any one of three possible mechanisms, arterial gas emboli, venous obstruction or autochthonous bubble formation. The transient hypertension which in three cases

reached very high levels could have been caused by a mechanism similar to that described in cats receiving arterial gas emboli to the brainstem as described by Evans et al. (1981). Lesser rises may also result from increased peripheral resistance caused by vascular obstruction. The subsequent hypotension seen in some of these and other dogs may reflect a loss of peripheral sympathetic tone in association with the cord DCS or a reduction in cardiac output. Several cases showed ECG changes compatible with ischaemia.

The fall in blood pressure and haemoconcentration reflects the severity of systemic disturbance. Fluid infusion is the essential method for correcting the haemoconcentration (Cockett et al.,1979); this incidentally corrects the blood pressure. The fluid supplements over the period following onset of DCS were similar in each group but failed to completely correct the haematocrit in the 1.0 bar group. A markedly elevated haematocrit with the consequently increased viscosity must impair tissue perfusion.

As far as possible the physiological variables which could influence recovery were controlled. However there was a tendency for factors such as blood pressure and thus cerebral perfusion pressure, haematocrit and arterial PO_2, during the pretreatment and early treatment phases to favour perfusion and oxygenation in the higher oxygen treatment groups. The pretreatment group mean haematocrit was the only relevant variable significantly different between treatments. However, neither group means nor individual haematocrit correlated with recovery at 15 or 120 min (Recovery at 120 min = 163.4 - 2.3 Hct with $R = 0.24$ ($p > 0.1$)). With the exception of pretreatment haematocrit, analysis of covariance using various combinations of the physiological variables failed to alter the level of significance of between group differences for SEP recovery. Pretreatment haematocrit reduced the level of significance to $p < 0.1$. It may be that the therapeutic measures taken during the surface interval and early treatment plus the exclusion criteria were effective in removing any clear association with lack of recovery.

Continuous exposure to high partial pressures of oxygen will lead to oxygen toxicity. If these were having a detrimental effect

on the recovery of damaged cord tissue it should show as an increased deterioration in the high oxygen groups as exposure continued. The mean deteriorations for the 1.5 to 3.0 bar groups were: 11, 13, 11 and 11 percent respectively (SE2 - 5). The mean for the 1.0 bar group was distorted by one case with a 58 percent deterioration otherwise the mean would have been the same as the others. Therefore there was no indication of oxygen toxicity. It is noteworthy that the only 5 dogs to experience no deterioration during treatment were in the groups treated with 2.0 bar oxygen or greater.

Interpretation of findings in the spinal cord sections was confounded by the history preceding their fixation. While changes could be attributed to the initial decompression insult it might be modified by the subseqeunt compression treatment; the fact of their final decompression also subjected them to a second insult. Two hours of air breathing at 5 bar (1.0 bar PO_2 group) could result in DCS, but breathing 60 percent oxygen (3.0 bar PO_2 group) makes DCS less likely. Therefore without knowing the event whichcaused the lesions, no differentiation between groups would be valid because of the varied risk of DCS at the end.

SECTION 10

PRESSURE AND TREATMENT

PRESSURE AND TREATMENT

10.1 PREAMBLE

From earlier work by Leitch et al. (1984a) it had been shown that pressures greater tha 2.8 bar did not improve the treatment of cerebral arterial gas embolism. Similarly Barnard and Hanson (1973) had found an optimal treatment pressure for mice with DCS, between 3.0 and 3.5 bar. It was now planned to see whether with PO_2 of 2.0 bar, additional pressure beyond the presumed threshold would improve the outcome of treatment.

10.2 METHOD

Dogs weighing between 10.0 and 14.5 kg were used in the final data pool. They were assigned to one of four treatment groups according to their weight. This ensured that the group mean weights were similar (range 11.3 to 12.1 kg). The treatments included three with PO_2 of 2.0 bar and ambient pressures of 3,5 and 7 bar and a fourth group breathing oxygen at 2.8 bar. The last group was included to provide a comparison with the generally accepted standard treatment. The desired PO_2 was obtained by providing 66, 40, 29 or 100 percent oxygen in nitrogen mixtures to the ventilator. The experiments were cycled so that after each series of four treatments the next replication began one place to the right.

The dive protocol was streamlined and all dogs were compressed to 10.0 bar (300 ft) at a rate of 75 ft min^{-1} while breathing air. They remained at 10 bar for 15 min before being decompressed at 60 ft min^{-1} to 60 ft and at about 45 ft min^{-1} from there to the surface. Dogs which did not show SEP changes within 30 min of surfacing were given a further 9 min at 10 bar. One dog in each group required a second dive. Mean ascent time was about 5.5 min (range 5.0 - 5.7 min). Recompression for treatment began 15 to 17 min after the diagnosis of spinal cord DCS was made.

The maintenance of dogs developing hypotension during the pre-treatment surface interval was improved by giving 8 percent sodium

bicarbonate to correct the acidaemia before giving the lactated Ringers solution. The same six exclusion criteria were applied in this experiment and led to the elimination of 12 cases from the final data pool.

After the dogs were decompressed at the end of the experiment the spinal cords were removed within 30 min of death from those dogs in the low pressure groups. The cords from the 3 and 2.8 bar groups were fixed in 10 percent phosphate buffered formalin (4% W/V formaldehyde). The low pressure groups alone were used because there was little risk of DCS from the final decompression. Thus any changes could reasonably be attributed to the initial decompression and have some bearing on recovery during treatment.

The cords were cut into 7 segments, cervical, 4 thoracic and 2 lumbar segments. These in turn were sectioned and 3 or 4 sections stained with haematoxylin and eosin. The sections were scrutinised for gross changes and for extent of haemorrhage. Each section was scored by the number and size of haemorrhages. Each haemorrhage was approximately graded 1 to 4: 1 - < 10 RBC, 2 - 10 to 20 RBC, 3 - 20 to 40 RBC and 4 - > 40 RBC. Each section was then scored for grey and white matter by multiplying each grade by its frequency. The mean section score was then calculated for the four main cord segments: cervical, upper thoracic, lower thoracic and lumbar.

10.3 SYSTEMIC CHANGES

The earliest change indicating DCS was again a reduction in EEG amplitude. However only 50 percent of cases were affected in this series (Table 27). The range of onset times was 2 to 17 min after surfacing. Cerebrospinal fluid pressure (CSFP) rose in 13 cases to levels shown in Table 28. There were 5 cases where CSFP rose in the absence of EEG changes and 2 cases where EEG changed without a CSFP rise. In only one case did the CSFP rise begin before the EEG change. The onset time for the CSFP rise was 3 to 18 min. There was no systematic association between CSFP rise and reduction in SEP amplitude.

Thirteen cases showed a rise in right ventricular pressure (RVP)

to as high as 170/0. In no cases did this precede the CSFP rise, in 4 cases the rises were coincident and in 4 cases the RVP rise was later. The remaining 5 were not associated with a significant CSFP rise. The pattern of change in RVP and CSFP during the pretreatment interval and treatment were similar to that seen previously (Table 28).

During the pretreatment interval only 4 dogs had an increase in systolic blood pressure of more than 20 mm Hg above any pre-diagnosis pressure (Tables 27 and 28). They all developed pressures in excess of 200 mm Hg but none reached 300 mm Hg. While these pressures were transient, in no case did the systolic pressure in these or the other cases fall even transiently below 100 mm Hg during the pretreatment interval. Compression caused a transient fall in mean blood pressure of up to 70 mm Hg in 13 cases.

TABLE 27

EVENT TIMES DURING DECOMPRESSION SICKNESS

Pressure (bar)	3.0	5.0	7.0	2.8	F-ratio
EVENT					
Surfacing to D	15 ±3	18 ±5	10 ±3	16 ±4	0.80
D-1 to D	4 ±1	4 ±1	4 ±1	5 ±1	0.86
Last SEP to Tr	1 ±1	2 ±1	2 ±1	2 ±1	0.22
RVP ↑	(3)11	(3)9	(2)14	(5)12	-
CSFP ↑	(4)15	(2)8	(4) 9	(3) 8	-
EEG ↓	(3)10	(1)8	(4) 6	(2) 3	-
$\overline{BP}$ ↑	(3)23	(0)-	(0)-	(2)24	-
$\overline{BP}$ ↓	(0)-	(0)-	(0)-	(0)-	-

Times in minutes shown as mean ± 1 standard error. Figures in parenthesis indicate numbers of dogs. D - diagnosis of DCS in the SEP, D-1 - last normal SEP. Tr - start of treatment.

Cerebral perfusion pressure calculated as the difference between CSFP and mean blood pressure is shown in Table 28. Heart rate increased up to 45 beats min^{-1} in 13 cases and was unchanged in 7 during the pretreatment phase. It returned to control levels during treatment. The mean rise was 12 beats min^{-1}.

TABLE 28

CARDIOVASCULAR VARIABLES

Pressure (bar)	3.0	5.0	7.0	2.8	F-ratio
MEAN BLOOD PRESSURE (mm Hg)					
Post-dive	118±5	122±10	112±5	120±8	0.39
Interval range	88-185	82-162	80-127	90-203	-
Pre-treatment	132±16	112±8	103±7	117±4	1.41
Change on Tr	-36(5)	-11(2)	-9(2)	-29(4)	1.39
Tr 15 min	130±8	144±12	133±4	121±11	1.16
Tr 120 min	114±4	119±5	123±7	115±7	0.53
RIGHT VENTRICULAR PRESURE (mm Hg)					
Post-dive	43/0	18/2	48/2	29/0	1.72
Interval range (syst)	20-170	12-34	10-110	18-115	-
Pre-treatment	61/4	25/1	54/1	53/1	0.81
Tr 15 min	72/1	20/2	50/3	31/2	1.37
Tr 120 min	29/4	19/3	42/2	24/0	1.70
CEREBROSPINAL FLUID PRESSURE (mm Hg)					
Post-dive	12±4	14±3	11±5	19±5	0.72
Interval range	1-22	2-22	1-28	5-56	-
Pre-treatment	10±4	11±4	10±3	20±4	1.50
Tr 15 min	10±3	11±5	21±8	17±7	0.80
Tr 120 min	10±3	18±9	23±8	18±7	0.67
CEREBRAL PERFUSION PRESSURE (mm Hg)					
Post-dive	106±7	108±9	101±1	101±5	0.27
Pre-treatment	122±13	101±6	93±8	98±6	2.00
Tr 15 min	120±7	133±8	112±8	104±14	1.76
Tr 120 min	104±6	101±12	100±8	97±3	0.08

Mean blood pressure = diastolic BP + 2/3 pulse pressure. Figures in parenthesis indicate numbers of dogs.

Variable amounts of fluid were given after the diagnosis of DCS (Table 29). They were effective in maintaining blood pressure and reducing the expected rise in haematocrit to a mean of 2.2 percent (Table 29). In only three cases did the increase exceed 5 percent and 15 cases showed a rise of only 3 percent or less.

A marked respiratory acidaemia occurred during the pretreatment phase (Table 30). Five dogs had an arterial pH of less than 7.3 which was caused by an elevation in arterial PCO_2. In 6 dogs $PaCO_2$ exceeded 39 mm Hg and in 3 of these it was 45 mm Hg or more. The 6 hypercapnic dogs were also hypoxaemic with a PaO_2 less than 85 mm Hg before treatment. The infusion of bicarbonate and compression resolved these conditions.

Up to the start of treatment the only variables which were significantly different between the group means were the arterial PCO_2 and PO_2. This indicated a significant pulmonary gas exchange problem in the 2.8 bar treatment group.

TABLE 29

HAEMATOCRIT AND FLUID BALANCE

Pressure (bar)	3.0	5.0	7.0	2.8	F-ratio
Hct Control (%)	44 ±2	44 ±1	43 ±1	45 ±1	0.66
Pre-Tr	47 ±3	47 ±2	43 ±2	47 ±1	1.02
Tr 40 min	49 ±3	47 ±2	43 ±1	45 ±2	1.36
Tr 80 min	46 ±2	45 ±2	44 ±1	45 ±2	0.26
Overall Fluid Balance (ml)	77 ±71	140 ±51	108 ±26	4 ±48	1.27
Fluid-in in Tr (ml)	190 ±46	186 ±42	96 ±20	100 ±27	2.15
Urine Output (ml)	178 ±55	104 ±12	146 ±40	140 ±30	0.65

Data given as mean ± 1 standard error. Tr - treatment.

TABLE 30

ACID-BASE AND GAS ANALYSIS

Pressure	3.0	5 0	7.0	2.8	F-ratio
ARTERIAL pH					
Control	7.39±0.01	7.37±0.01	7.39±0.02	7.38±0.01	0.62
Pre-Tr	7.35±0.02	7.34±0.02	7.34±0.03	7.31±0.03	0.49
Tr 40 min	7.34±0.02	7.41±0.02	7.38±0.05	7.38±0.02	0.94
Tr 80 min	7.37±0.02	7.40±0.02	7.37±0.04	7.37±0.01	0.47
ARTERIAL PCO_2 (mm Hg)					
Control	33±1	34±1	33±2	35±1	0.92
Pre-Tr	32±2	38±2	38±3	43±3	3.32*
Tr 40 min	36±3	34±2	40±5	38±2	0.72
Tr 80 min	37±3	35±3	41±4	36±1	0.64
END -TIDAL FCO_2 (Percent)					
Control	3.4±0.3	3.8±0.4	3.3±0.3	3.7±0.3	0.30
Pre-Tr range	2.2-4.1	2.1-5.3	1.8-4.1	2.5±4.6	-
Pre-Tr	3.7±0.1	3.6±0.4	3.4±0.4	3.7±0.3	0.22
Tr 40 min	4.4±0.3	4.4±0.3	4.7±0.3	4.6±0.2	0.31
Tr 80 min	4.5±0.3	4.6±0.1	4.5±0.3	4.2±0.1	0.61
ARTERIAL PO_2 (mm Hg)					
Control	94±3	96±2	92±3	90±3	1.02
Pre-Tr	108±10	99±6	89±4	74±9	3.33*

Data shown as mean ± 1 standard error. Tr- treatment. * Under F-ratio indicates a significance of $P < 0.05$.

10.4 SPINAL EVOKED POTENTIALS

Examples of EP changes in two dogs are given in Figures 29 and 30. The first identified SEP lesions in the 20 dogs in the final data pool included 13 left lumbar and 7 right lumbar lesions (Table 33). These SEPs were used for diagnosis and assessment of recovery. The loss of SEP amplitude ranged between 29 and 100 percent by the start of treatment. At the start of treatment there was no significant difference in severity between the groups (Table 31 and 33).

The time from surfacing at which SEP change was identified ranged

between 2 and 30 min. There was no significant difference between the group means inspite of the shorter mean onset time in the 7 bar group (Table 27). The extent of the change leading to diagnosis (D-1 to D) ranged between +8 and -45 percent of control (Table 31). Occasionally an increase in amplitude was seen as inhibitory fibres ceased to function before there was a generalised loss of amplitude. The interval between the last normal SEP and the diagnostic SEP was less than 5 min in all cases (Table 27). The check on diagnostic perception of comparing the penultimate normal SEP (D-2) with the last presumed normal SEP (D-1) showed no difference between the group means (Table 31). In 2 cases in the 7 bar group onset time was very short so the prediagnostic SEPs were recorded at pressure.

The progression of the SEP amplitude loss between diagnosis and start of treatment (D to Pre Tr) is shown in Table 31. Three cases showed a stable SEP loss prior to treatment; one in the 3 bar group and two in the 7 bar group. The remainder were showing a progressive deterioration. The interval between the last pretreatment SEP and the start of compression therapy varied between 0 and 6 min (Table 27). Four dogs showed a further SEP loss over compression. The additional losses were 36% (3 bar), 21% (5 bar), 2% and 11 (2.8 bar) with respective intervals before compression of 1, 6, 2 and 2 min.

Recovery of SEP amplitude was rapid in the first 15 min of treatment (Table 32) and ranged between 1 and 100 percent. Although the 3 bar group led recovery at 15 min there was no significant difference between the group means. The 3 and 2.8 bar groups showed a further improvement in group means by 40 min. This led to a significant difference between the group means ($P < 0.05$). The significant difference was preserved at 80 min but lost by 120 min, as the 3 bar group entered a slow deterioration while the 5 bar group continued to improve. The 7 and 2.8 bar groups remained stable. The decline in the 3 bar group was largely due to one case which lost 70 percent of its 100 percent peak at 15 min. The rest of the group all showed a small reduction in amplitude. Two dogs contributed to the continued improvement of the 5 bar group, and one dog to the late fall in the 2.8 bar group. Ten dogs did not show more than a 4 percent deterioration from their

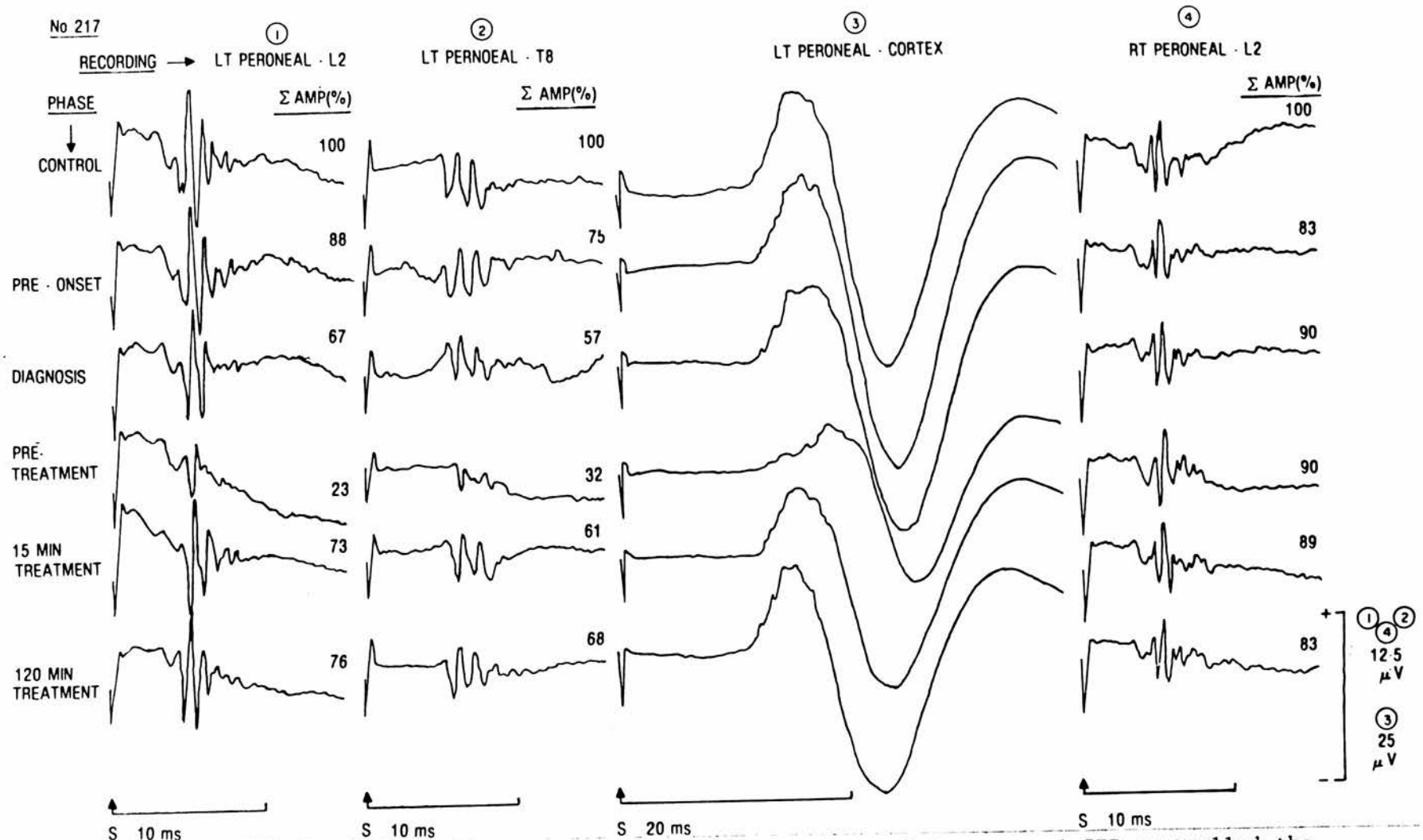


Figure 29. No. 217 - Spinal and cortical evoked potentials. Left peroneal SEP controlled the experiment.

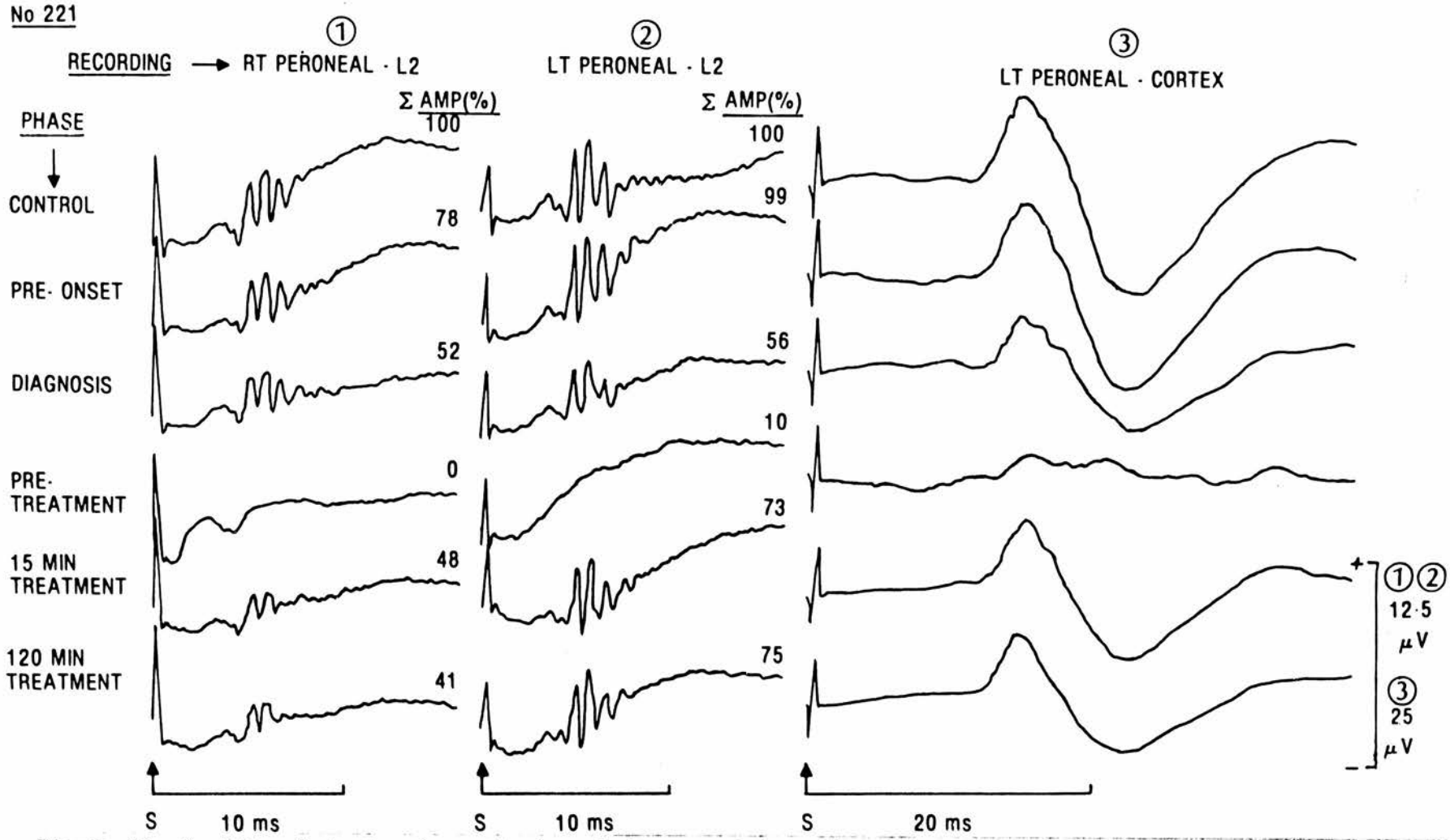


Figure 30. No 221 - Spinal and cortical evoked potentials. The right lumbar SEP controlled the experiment although the lumbar cord was affected bilaterally.

peak recovery. The 120 min of treatment ended with no significant difference between the groups.

The individual peak recovery times covered the entire treatment period. Using all the available SEP data showed the group mean peak recovery times to be 54, 46, 60 and 81 min (F ratio 1.31). The mean SEP recovery at these times was 91, 80, 54 and 63 percent (SE 6 to 12 and F ratio 3.46*). The subsequent deterioration was similar in the four groups at 24, 18, 25 and 20 percent.

TABLE 31

CHANGES IN SPINAL EVOKED POTENTIALS

Pressure (bar)	3.0	5.0	7.0	2.8	F-ratio
TIME PERIOD					
D-2 to D-1	+3 ±4	+3 ±2	-1 ±1	-4 ±3	1.42
D-1 to D	-27 ±7	-7 ±5	-17 ±3	-4 ±11	2.08
D to Pre-Tr	-54 ±15	-47 ±14	-60 ±15	-65 ±14	0.29
Pre-Tr loss	86 ±7	70 ±13	84 ±12	81 ±8	0.45

Change in SEP as a percent of control shown as mean ± 1 standard error. D-2 - penultimate normal SEP, D-1 - last normal SEP, D - diagnostic SEP, Tr - treatment.

TABLE 32

SEP RECOVERY AS PERCENT OF LOSS

Pressure (bar)	3.0	5.0	7.0	2.8	F-ratio
TIME PERIOD					
at 15 min	75 ±11	55 ±12	31 ±13	32 ±9	3.11
at 40 min	89 ±10	53 ±14	31 ±13	46 ±8	4.20*
at 80 min	80 ±10	58 ±13	27 ±11	50 ±9	3.89*
at 120 min	67 ±13	62 ±13	29 ±8	42 ±12	2.39

Recovery of SEP during treatment expressed as percent of loss shown as mean ± 1 standard error. *Under F-ratio column shows significance at $P < 0.05$.

The extent of CNS involvement as far as it can be assessed is shown in Table 33. This includes the onset times for EEG changes as well as the pretreatment SEP amplitude loss. Expressing the number of left and right lumbar, and left cervical SEPs affected as a percentage of the available recordings gave group means of 50, 40, 50 and 60 percent.

10.5 DISCARDED DATA

Twelve dogs were discarded because they did not satisfy the criteria for inclusion. Three required second dives and four required controlling dives to prevent cardiovascular collapse. The diagnosis was missed in 4 cases which resulted in excess delay to treatment, 4 cases showed no recovery, the remainder experienced one each of prolonged hypotension as low as 50/34 for 13 min, physiological instability, spontaneous recovery and random SEP changes. This large loss was in part due to the learning needs of potential successors to the author.

10.6 PATHOLOGY

Three dogs had macroscopic haemorrhages in the cord. Number 202 had gross haemorrhage over the left lateral column in the cervical cord, No. 204 had petechial haemorrhages over the thoracic cord and No. 234 had gross haemorrhage over the cervical cord and petechial haemorrhages over the lumbar cord (Table 33 and 34).

Cords were removed from 9 dogs in the experiment. A control dog which was prepared in the same way for a control study but was not dived was added, as was the cord from a case of untreated DCS.

Sections showed a spectrum of haemorrhages from nil to frequent and macroscopic, as seen in No. 204 (Table 34). Additional changes seen were instances of vascular congestion and a teased appearance. An estimate of the extent of haemorrhage is shown in Table 34.

A small number of haemorrhages were seen in the thoracic cord of the control dog. This suggests a need for a greater number than 2 or 3 per section to indicate pathology. For the most part the majority of haemorrhages occurred in the grey matter except in dogs 204 and 234.

TABLE 33

THE EXTENT AND SEVERITY OF CNS DECOMPRESSION SICKNESS

EP	LPL	LPT	LPC	RPL	RPT	RPC	LMC	EEG (Time)
DOG								
200	100	?	100	[100]	?	100	0	-
201	[100]	100	100	52	?	?	0	14
202	[65]	>41	>29*	0	24	14*	>20*+	9
203	75	69	47	[76]	?	?	0	8
204	[90]	100+	100	86	>67+	100	0	-
211	[98]	85	100	11	>23	?	66	7
213	0	0	?	[52]	58	?	0	-
216	[95]	?	96	85	100	100	0	-
217	[77]	68	50	0	0	?	0	-
218	[29]	100	100	0	100	100	0	9
220	24	13	27*	[36]	35*	36	0	3
221	90	83	82	[100]	?	?	0	-
222	[99]	?	100*	89	?	?	0	17
224	[90]	100	95	76*	71*	100	0	2
225	84	97	100	[93]	100	100	0	3
231	[100]	100	100	85	?	?	0	-
232	>69	?	>46	[90]	?	100	0	-
233	[65]	?	55	37	?	>58	>20*	4
234	[59]+	?	68	74+	?	?	95*+	2
235	[93]	?	100	89	?	100	0	-

Data are presented as percent of control SEP lost at the start of treatment. [ ] -principle and controlling SEP, ? - no record, * - no recovery at 120 min, + - cord haemorrhage at post mortem. Evoked potentials are LPL - left peroneal lumbar, thoracic and cervical, RPL - right peroneal lumbar, thoracic and cervical, LMC - left median cervical. Figures in the EEG column are onset times in minutes.

TABLE 34

FREQUENCY AND DISTRIBUTION OF HAEMORRHAGE

SITE	LUMBAR		LOWER THORACIC		UPPER THORACIC		CERVICAL	
DISTRIBUTION	G	W	G	W	G	W	G	W
DOG								
CONTROL	0	0	1	0	3	0	0	0
DCS No Tr	0	0	5	5	2	20	37	3
201	3	0	7	0	0	0	0	0
202	0	0	10	7	6	11	3	0+
203	4	0	9	1	11	0	12*	4*
204	41	43	13	41+	12	9+	16	153
231	1	0	1	0	4	1	0	0
232	1	2	1	0	2	0	0	0
233	1	0	2	0	8	0	33	2
234	3	11+	1	3	3	7	14	41
235	0	1	0	5	4	0	2	0

Mean section haemorrhage expressed as the product of frequency and grade for each main cord segment, divided into grey (G) and white (W) matter. Dogs were; undived control, untreated DCS, 4 dogs from the 3 bar group and 5 dogs from the 2.8 bar group. + - macroscopic subarachnoid haemorrhages. * Unilateral haemorrhage.

TABLE 35

INDIVIDUAL SEP RECOVERY AT 120 MIN

3 Bar Treatment

DOG	201	202	203	204
SEP SITE	LPL	LPL	RPL	LPL
% RECOVERED	84	97	82	44

2.8 Bar Treatment

DOG	231	232	233	234	235
SEP SITE	LPL	RPL	LPL	LPL	LPL
% RECOVERED	55	18	68	10	60

Data shown as percent of SEP loss recovered at 120 min. LPL - left peroneal lumbar, RPL - right peroneal lumbar.

Three dogs (202, 233, 234) experienced a loss of cervical SEP which did not return during treatment. The cervical cords of 202 and 234 showed extensive subarachnoid haemorrhage, while those of 233 and 234 showed extensive microscopic haemorrhages. Comparing the amount of lumbar SEP recovery at 120 min (Table 35) with the extent of lumbar cord haemorrhage shows only a correlation between the poorest recovery in each group and the greatest amount of haemorrhage.

10.7 DISCUSSION

At the start of treatment the four treatment groups were physiologically similar except that the 2.8 bar group displayed a respiratory acidosis with hypoxaemia. This was indicative of a pulmonary perfusion problem although it was not particularly reflected in the pretreatment RVP. The groups had similar degrees of spinal cord DCS. During treatment a large proportion of the recovery had occurred by 15 min with a peak of recovery at around 60 min. Twenty minutes either side of this peak the groups were significantly different from one another. By 120 min the difference was no longer significant. The hypothesis that additional pressure would not improve recovery once a pressure threshold had been passed and an optimum PO_2 established was proven. The appearance was also given that the rate of recovery when using a PO_2 greater than 2.0 bar might be slower although the same end point might be reached.

Only three dogs recovered their SEP loss completely but none of the recovery was sustained. Comparisons of this and the prevous study suggested that better control had been established over the model. The systemic DCS now seemed less severe. The rate of EEG loss fell from 72 to 55 percent, and the rate of principal SEP loss fell from 71 to 50 percent. However the mean SEP loss rose from 64 to 80 percent. There was a lower incidence of hypertension, down from 36 to 25 percent, and none of these approached a systolic pressure of 300 mm Hg where previously 3 dogs had exceeded that pressure. There was less acid-base disturbance, the haematocrits were largely contained, and there were no cases of hypotension in the pretreatment period inspite of a smaller volume of fluid being infused. The number of instances of transiently reduced blood pressure during compression fell from 88 to 65 percent possibly indicating less free systemic gas. The level of recovery gained by the best groups in each study was similar inspite of a greater SEP

loss in this study and more severe systemic disturbance in the former study. The fact that ten dogs did not show more than 4 percent reduction from peak recovery coincides with the observation in the previous study that those which did not deteriorate were confined to the 2.0 bar or higher oxygen groups. The reduction from peak amplitude was similar in the 4 groups but was twice that seen in the previous study.

Although there was no significant difference between the group mean onset times, it is notable that the 7 bar group with the shortest onset time had the lowest recovery. There was again a correlation between onset time and recovery. The least squares regression equation was

$$Y = 15.50 + 2.35t$$

where Y was the percent recovered and t was onset time in minutes ($R = 0.51$, $P < 0.001$). Separating recovery into those achieving less than 40 percent and those achieving more than 60 percent at 120 min gave mean onset times of 6.7 and 20.2 min ('t' test $P < 0.001$). So in this study where all treatments are expected to be equally effective it was confirmed that early onset time militates against good recovery where there is at least a 15 min delay before recompression. Again there was no difference in the percent of SEP loss at 75 and 78 percent respectively. There was no identifiable association with systemic changes, cerebral DCS, haemorrhages or extent of cord DCS to account for this relationship.

SECTION 11

ELECTROCARDIOGRAPHIC CHANGES IN DECOMPRESSION SICKNESS

ELECTROCARDIOGRAPHIC CHANGES IN DECOMPRESSION SICKNESS

11.1 PREAMBLE

Electrocardiograph changes have only rarely been reported in divers suffering from decompression sickness (DCS) (Burch, 1979; Halpern and Greenstein, 1981; Kizer, 1980). This probably reflects the infrequency of ECG recording in sick divers. Such changes have been seen in compressed air workers (McCallum, 1968; Zannini, 1967). McCallum listed amongst serious signs and symptoms, angina and irregular pulse. While Zannini reported a wide spectrum of ECG findings: pulmonary P waves, notched P waves, depression of the S-T segment, flattening or inversion of T waves, lengthening of P-R interval, right axis deviation, bundle branch block and A-V blocks. Changes suggesting early myocardial injury suggested by S-T segment and T wave changes have also been reported by Burch, (1979). Animal studies of venous gas emboli have been reported to cause diaphasic T waves and flattening or inversion of T waves (Butler and Hills, 1979). Bubbles have also been seen post-mortem in coronary arteries (Behnke et al. 1936). First degree A-V block and premature ventricular contractions were seen in two divers with DCS (Halpern and Greenstein, 1981; Kizer, 1980).

11.2 METHOD

The 21 cases described were drawn from a total of 77 dogs reported in previous studies. The ECG was recorded from four limb leads and a thoracic electrode at the V_5 position. The electrodes were stainless steel 21 guage needles placed subcutaneously. Lead II was recorded continuously except when the 7 other possible leads were recorded at intervals.

The ECGs were analysed using Ettinger and Suter (1970) as a guide to interpretation. The 21 cases selected had unequivocal changes associated with systemic and neurological DCS. These were are least partially reversible with compression. The changes were correlated with the simultaneously observed systemic observation.

Four categories of change were sought. Evidence of right or left

atrial strain: P wave amplitude more than 0.4 mV or an increase in P wave amplitude, P-R segment depression, P wave prolonged and notched, S wave enlarged. Evidence of supraventricular conduction defects: P-R interval exceeding 0.13s, dropped beats. Evidence of myocardial ischaemia: prolonged QT_C interval ($QT_C = \frac{QT}{\sqrt{R-R}}$), deep or absent Q wave, small R, widening or slurring of Q RS, S-T depression exceeding 0.1 mV or elevation of more than 0.15 mV, flattening or inversion of T wave, tall or notched T wave exceeding 25 percent of R. Evidence of arrhythmias: premature A-V nodal rhythmn, A-V dissociation, irregular P waves, ventricular tachycardia, bigeminal or trigeminal rhythmn, unifocal or multifocal premature ventricular contractions.

11.3 RESULTS

The 21 cases with ECG changes had DCS of varying degrees of severity. Ten could be classed as having severe DCS based on gross cardiovascular changes. These were a systolic BP exceeding 250 mm Hg or hypotension with a systolic BP below 100 mm Hg, or a rise in right ventricular sytolic pressure (RVP) of more than 20 mm Hg. All 10 dogs had a rise in RVP of at least 10 mm Hg, 5 had a rise of more than 20 mm Hg and two of these reached 115 and 144 mm Hg, both fourfold increases. Three each were hypertensive or hypotensive. Eight of these 10 dogs also had a severe irreversible loss of EEG amplitude as a result of DCS.

All cases showed an elevation of cerebrospinal fluid pressure. Half the cases showed between none and relatively small changes in BP and at least 6 of these showed no real change in RVP. Fourteen dogs showed a loss of EEG amplitude. Of the 7 which retained a normal EEG, 2 were classed as having severe DCS. Arterial blood samples taken during the acute DCS phase showed an increase in haematocrit of at least 5 percent in 6 dogs (maximum increase 16 percent), a pH of less than 7.3 in 6 dogs (3 also had raised haematocrits), and an arterial PO_2 below 65 mm Hg in 4 dogs. Ringers lactate solution and bicarbonate were given to correct haemoconcentration and acidosis. Examples of ECG changes are shown in the figures. The legends give the times and materially altered physiological variables for each ECG shown. All traces were Lead II unless otherwise shown. Increases in P wave voltage of between 0.15 and 0.26 mV raised P wave amplitude to over 0.4 mV in

5 cases (Figure 31). In two of these there was no indication of an increased RVP. There were smaller amplitude increases in 5 other dogs, and 3 instances of P-R depression (0.05 to 0.10 mV) (Figure 31).

There were no instances of prolongation of the P-R interval in excess of 0.13s. However there were 2 cases of apparently dropped beats arising one as a result of an irregular P wave (Figure 32) and the other as a result of a wandering pacemaker (Figure 33). Both occurred in association with changes suggestive of myocardial ischaemia and both episodes were brief and reverted spontaneously to normal rhythm. In Figure 33 the heart rate was precisely halved 14 min after the onset of systemic DCS.

Examples of ECGs suggestive of myocardial ischaemia are shown in Figure 34. Corrected QT interval was prolonged between 0.02 and 0.07s in 15 cases, the R wave was attenuated by 0.15 to 0.6 mV in 5 cases and the S-T segment was depressed by 0.15 mV in 2 cases and elevated by 0.20 and 0.40 mV in 2 cases. The T waves were flattened or inverted in 15 cases and were increased by up to 0.6 mV in 3 cases to be at least 25 percent of the R wave amplitude.

There were only 2 instances of arrhythmias arising without other ECG changes. Ten dogs showed ventricular arrhythmias. These included 2 cases of ventricular tachycardia, 4 cases of bigeminal rhythm, 3 or multifocal and 2 of unifocal premature ventricular contractions (Figure 35). Two different arrhythmias occurred in the same dog.

It should be noted that by the end of each study 8 ECGs had not returned completely to the control ECGs.

11.4 DISCUSSION

Electrocardiographic changes suggestive of right heart strain, myocardial ischaemia and functional derangement were seen. All cases had DCS identifiable by systemic changes as well as spinal cord DCS.

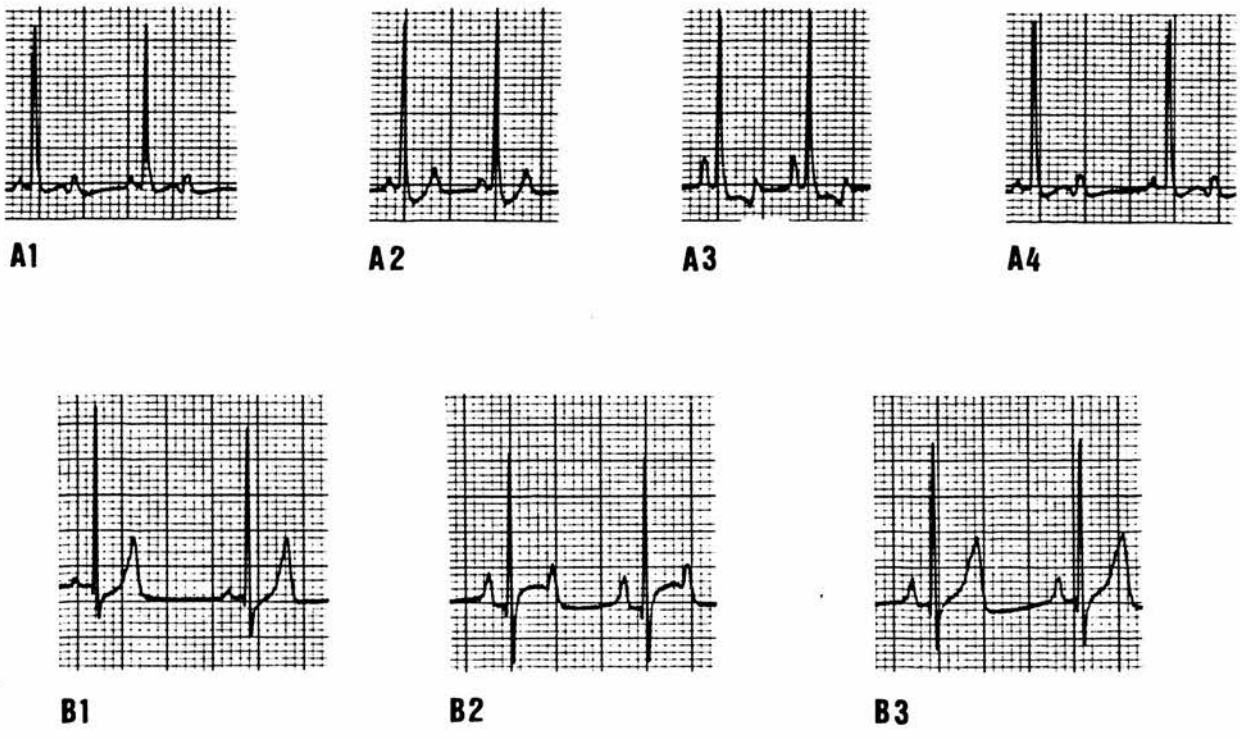


Figure 31. ECG changes in decompression sickness. S-T, T and P wave changes. A1 to 4 shows a sequence of changes including S-T depression in A2 and A3. There is P wave peaking in A3. After recompression all was restored to normal in A4.

A1 - Control	BP 130/100	HR 118	PCV 45	pH 7.35
A2 - 12 min post-DCS	350/180	148	61	7.28
A3 - 2 min post-recompression	125/ 90	148	48	7.38
A4 - 88 min post-recompression	125/ 90	94	-	-

B2 shows peaking of P and S-T elevation with a reduction in R and an increase in S suggestive of right axis deviation.

B1 - control	BP 150/120	HR 84	PCV 39	pH 7.37
B2 - 10 min post-DCS	112/ 65	100	50	7.28
B3 - 17 min post-recompression	130/ 94	91	37	7.29

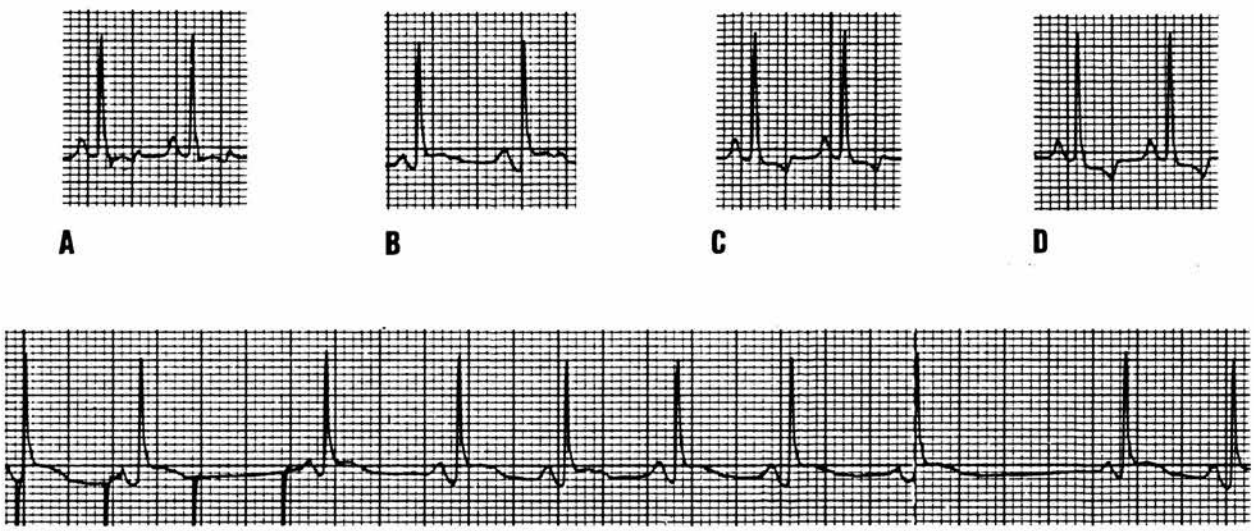
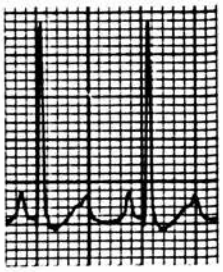
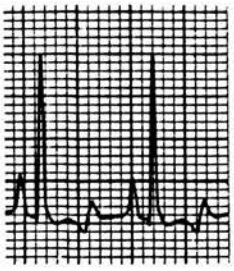


Figure 32. ECG changes in decompression sickness. S-T, T and P wave changes. B and C show S-T segment and T wave changes which continued after recompression in D. There is P-R depression in B and E. E shows a slightly irregular P wave with 2 prolonged recovery intervals. The P waves look similar and not ectopic. The 4 regular negative peaks are stimulus artifacts.

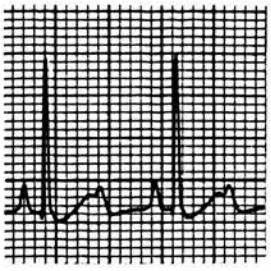
A - control	BP 180/145	RVP 24/ 4	HR 147
B/E-15/12 min post DCS	235/120	50/10	124
C - 29 min post recompression.	148/120	28/ 0	150
D - 58 min post-recompression	140/120	28/ 0	148



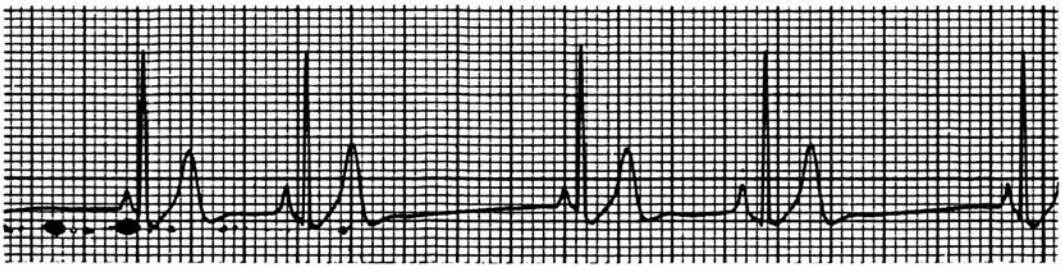
A



B



C



D

Figure 33. ECG changes in decompression sickness. S-T and P wave changes. B shows P wave peaking and S-T segment changes. D shows a transient bradycardia with a regularly occurring ectopic P wave followed by a prolonged recovery period.

A	- control	BP	144/108	HR	147
B/D	- 14 min post-DCS		200/120		143/73
C	- 45 min post-recompression		150/110		121

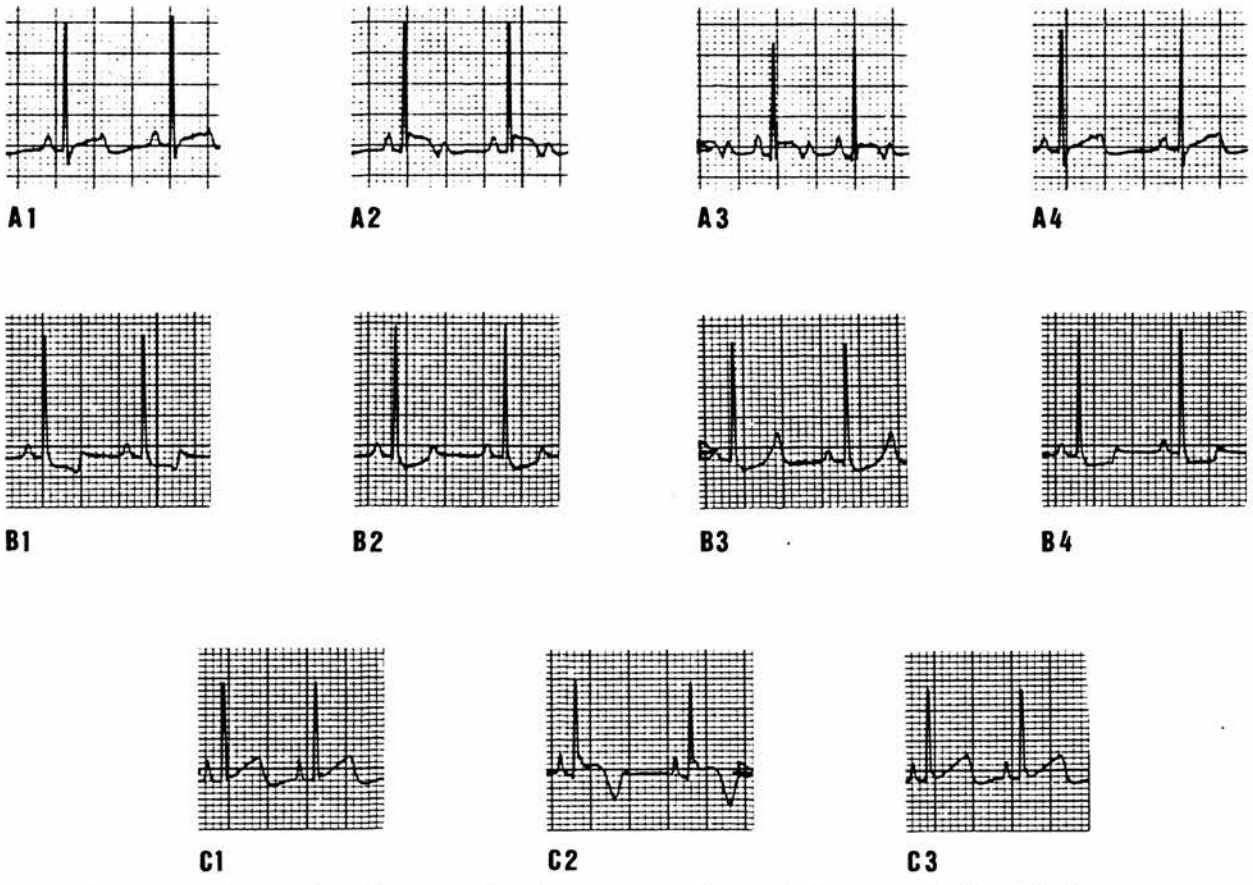


Figure 34. ECG changes in decompression sickness. S-T and T wave changes. A2 and 3 show S-T elevation with recovery in A4.

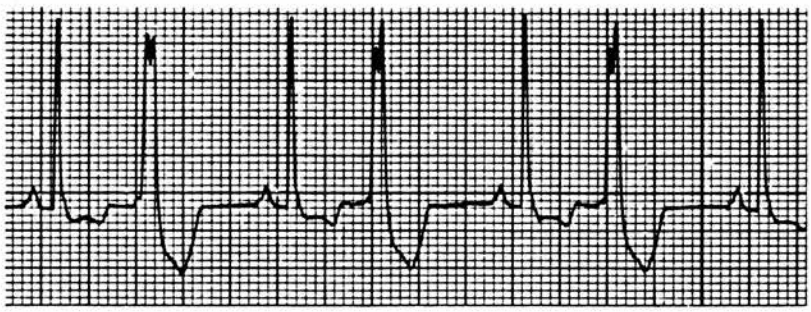
A1 - control	BP	140/112	HR	107
A2 - 13 min post-DCS		108/ 78		112
A3 - 2 min post-recompression		68/ 46		143
A4 - 88 min post-recompression		150/115		99

B2 and 3 show two stages of T wave changes which were reversed in B4 on recompression.

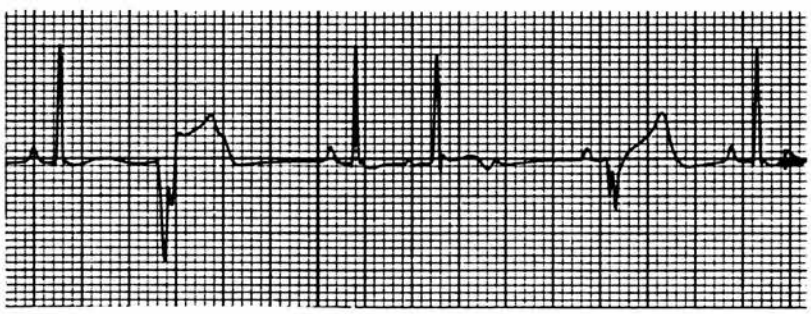
B1 - control	BP	135/110	HR	115
B2 - 14 min post-DCS		130/108		106
B3 - 4 min post-recompression		105/ 85		104
B4 - 33 min post-recompression		150/130		116

C2 shows S-T elevation with T wave inversion which recovered on recompression in C3.

C1 - control	BP	120/ 90	RVP	26/0	HR	127
C2 - 17 min post-DCS		90/ 45		38/0		101
C3 - 28 min post-recompression		125/100		12/0		121



A



B

C

Figure 35. ECG changes in decompression sickness. Arrhythmias. A shows a period of unifocal premature ventricular contractions with bigeminal rhythmn, B shows a period of multifocal premature ventricular contraction (Lead III) and C shows a period of ventricular tachycardia.

A - 5 min post-DCS	BP 100/65	RVP -	HR 147	PO_2 46 (13 min later)
B - 16 min post-DCS	120/95	24/5	100	pH 7.28
C - onset of DCS	320/250	48/4	250	PCV 64

The ECG indications of right heart strain were not necessarily associated with significantly increased right ventricular pressure or hypoxaemia. There were 4 such cases. There were another 5 cases with pulmonary hypertension or hypoxaemia which did not show ECG changes associated with right heart strain.

Indications of the compromising of myocardial oxygenation may result from severe hypoxaemia of which there were 4 instances. It seems unlikely that in situ myocardial bubble formation would occur in such a highly perfused organ. However coronary artery bubble embolism would be a possibility. There was abundant evidence of intravascular bubbling not least in the level of haemoconcentration seen in several cases inspite of intravenous fluids and in the pulmonary hypertension. These conditions may also cause cardiac arrhythmias.

Evans et al. (1980, 1981) point to three other possible sources of ECG changes resulting from central nervous system injury and activation by the autonomic nervous system. These include head injury, spinal cord compression and brainstem embolisation. Similar responses could also follow brainstem, cerebral and spinal cord DCS. Studies of acute cord compression produced sinus or nodal bradycardia, massive hypertension, premature AV nodal or ventricular beats with AV dissociation, ventricular tachycardia, bigeminal and trigeminal rhythms. In the DCS cases there was one case of nodal bradycardia. All cases were prepared with a low dose of atropine which might in some cases have blocked the bradycardia as was reported by Evans et al., (1980) using higher doses. there were several cases of transient hypertension, of which six out of seven had ventricular arrhythmias.

Air embolisation of the brainstem through the vertebral artery has been shown to produce a similar range of cardiovascular and ECG changes (Evans et al., 1981). There were three cases in this series where EEG amplitude loss was closely associated with ECG changes although this did not include an arrhythmia in one case. Only one of the three cases developed hypertension.

Evans et al. (1980) attribute the bradycardia to afferent nerve injury creating vagal activity through the medullary reflex pathway. They suggest that spinal afferent sympathetic nerve injury might cause diffuse stimulation of the heart and vasculature. This results in increased heart rate, contractile force and blood pressure causing a reactive vagal hyperactivity. The resulting sympathetic-parasympathetic imbalance causes arrhythmias. In the study of brainstem mechanisms they found that complete surgical and pharmacological autonomic blockade failed to stop the tachycardia and hypertension (Evans et al., 1981). As the catecholamine effects should have been blocked they postulated an unidentified humoral agent released from the brainstem. As no such blockade was present in the DCS cases an increase of stress released catecholamines could also have contributed to the changes seen.

The occasional clinical cases of ECG changes associated with DCS reported were not immediately reversed by compression treatment. In this series of animal observations 8 out of 21 cases did not return completely to normal after up to 2 hours of compression therapy. Very few ECGs are recorded from cases of DCS and there would seem to be valid reasons for increasing the frequency of such recording. Particularly as there was about a 27 percent incidence of ECG changes in this series covering a wide range of systemic derangement, and about 40 percent of the ECG changes were not immediately completely reversible.

SECTION 12

DISCUSSION

12.1 Evoked Potentials

12.2 The Dive

12.3 The Pathological Mechanism of Decompression Sickness

12.4 Factors in recovery

12.5 Treatment with Oxygen and Pressure

12.6 Delayed Recovery

DISCUSSION

12.1 EVOKED POTENTIALS

The method developed for studying spinal cord DCS by means of multiple evoked potentials proved effective in allowing diagnosis, a degree of localisation and quantification of the lesions without invasion of the spinal canal or neuraxis. The observations on the effects of varying stimulus and recording parameters largely corroborated those of earlier investigators. The comparison of the effects of chloralose and pentobarbital on CEP revealed a considerable depression in amplitude attributable to pentobarbital.

The comparison of anaesthetics did not include unanaesthetised animals so no comment can be made on how CEP or SEPs deviated from normal. In comparing these two anaesthetics Harding et al. (1979) observed that pentobarbital reduced the number of active cortical neurons when compared with chloralose. It has also been observed that barbiturate anaesthesia in low doses tends to facilitate CEP but that higher (surgical anaesthesia level) doses tend to depress CEP (Pimmel et al., 1976; Dafny, 1978; Nordwall et al.,1979). Dafny attributes this to an effect upon the reticular system. Abrahamian et al. (1963) also point to an extralemniscal influence but on the later waves. Other authors observed that in general only the late non-specific parts of the CEP were depressed (Clark and Rosner, 1973; Allison et al., 1963). These slightly conflicting observations may result from the maintenance of different levels of anaesthesia and the fact that all those observations which suggested that the early waves (< 100 ms) were unaffected, were made in man. The tentative observation that the late positive wave in the SEP recorded close to the root of entry might be affected by anaesthesia, may be supported by Robson's (1971) observation that presynaptic inhibition is potentiated by barbiturates leading to mono-synaptic reflex depression. No dogs in the choralose experiments were prepared for SEP measurement. However, it seems probable that relative to the unanaesthetised state and to chloralose anaesthesia, the SEPs were also depressed by pentobarbital as seen by Nordwall et al. (1979).

Rosner and Clark (1973) observed that pentobarbital caused a reduction in excitatory activity in cord and suppression of transmission in small fibres (cutaneous) in the antero-lateral columns at moderate doses. These findings are all largely in accord with those of Albe-Fessard et al. (1970) who compared these two anaesthetic agents.

Pimmel et al. (1976) also found that increasing stimulus and its duration increased CEP amplitude and that it was reduced by increasing rate. They found that durations greater than 5 ms and rates greater than 3 Hz distorted the CEP. Cracco and Bickford (1968) observed in awake humans that CEP amplitude plateaued beyond 0.1 ms stimulus duration, although they experimented with a duration of 0.3 ms and rates of 1 - 3 Hz. Matthews et al. (1974) saw that CEP amplitude continued to grow and latency to shorten, as stimulus increased up to about three times motor threshold. The cervical SEP was unaltered by rates up to 10 Hz although CEP was reduced. The findings in this study were generally in accord with these, although beyond 5 Hz there was a slight tendency for the late P wave amplitude in SEP to fall. Nordwall et al. (1979) successfully recorded the travelling waves at rates up to 30 Hz.

The effect of bandpass limits has been investigated by Desmedt et al. (1974). It was confirmed that the upper limit should not be less than 3 KHz. The lower limit used was 30 Hz which cost some CEP amplitude reduction but was necessary in order to view P_2 (latency 25 - 33 ms). This bandpass had little effect upon the SEP.

The key to revealing the cortical FFPs was the increased separation of the reference electrode from the active cortical electrode by placing it in the distal end of the nasal bones. Iragui-Madoz and Weiderholt (1977) also found this. They also observed that a large distance between active and reference electrode which crossed the cardiogenic electrcal field made EPs prone to ECG breakthrough. The problem of episodic ECG breakthrough was never entirely solved, although many approaches to earthing it with multiple needle earths and a chest plate earth were tried.

It was necessary to avoid tying the EP average to the ECG QRS complex because the decompression sickness sometimes caused severe arrhythmias which could prevent EPs being observed altogether. The alternative of increasing the numbers averaged would have entailed an unacceptable time penalty.

The increased complexity of the SEP seen with the bipolar configuration was preferred to the larger amplitude but less detailed SEP obtained with monopolar electrodes by others (Cracco, 1973 and Ertekin, 1978). As in this study, Ertekin (1978) and Sarnowski et al. (1975) observed that SEP amplitude and definition depended upon the proximity of the electrode to the cord. The driving of the electrode into the lamina essentially produced an epidural SEP. An additional advantage was the anchoring of the electrode so eliminating the possibility of movement artifact.

Complex analytical methods (John, 1974; Dill et al., 1976) were considered but as the examples of EP during cord DCS show, fine discrimination techniques were hardly necessary and the simple additive method proved satisfactory.

The 2°C deviation from the mean rectal temperature of about 38°C produced no observable change in the EP. Greater extremes do adversely affect EPs (Aunon et al., 1977; Budnick et al., 1981; Dubois et al., 1981).

The observation of the reduction of late slow P waves in SEPs after neuromuscular blockade have been seen before with d-Tubocurarine (Lindbolm and Ottosson, 1953). The late P waves clearly represent local events and have been temporally linked to segmental reflexes (Gelfan and Tarlov, 1955). In view of the failure to observe any change as a result of rigid joint fixation and the changes seen with muscle relaxation, it seems that the affected components may be muscle afferents.

The first three primary cortical waves P_1, N_1 and P_2 were observed to the exclusion of the later waves which were more variable. The

observed mean latencies in all groups studied were comparable with those observed in dogs by Norrsell (1966), Parker (1978a), Parker (1978b), Norrsell, in cord transection experiments, showed that the P_1N_1 components were transmitted ipsilaterally in the dorsal columns and in the dorsal part of the lateral funiculus. He also observed that waves with the latencies of P_2 and later were transmitted through both ipsilateral and contralateral ventral funiculi.

While remembering that species differences exist in the neuroanatomy (Arezzo et al., 1979), similar findings were reported by Simpson et al. (1981) in monkeys. Large diameter fibres in the dorsal columns contributed to waves of latency less than 40 ms and small diameter fibres in the antero-lateral columns contributed to latencies greater than 70 ms. The waves between 35 and 70 ms (P_2N_2) had a dual contribution from both columns. These findings are generally supported by human work which shows that cord lesions which cause the greatest reduction in the early CEP waves are associated with impairment of vibration and position sense while the lesser impairment of the $P_2N_2P_3$ waves is associated with loss of pain and temperature sense (Sances et al. 1978; Yamada et al., 1979; Dorfman, et al., 1980).

Between four and seven FFPs were commonly observed in the CEP, the majority preceded N_1. They could be observed bilaterally with a unilateral stimulus. They were most pronounced with median nerve stimulation which on occasion showed as many as 11 FFPs. The earliest observed was the stationary wave closest to the stimulus which was sometimes also seen in the SEP and is attributed to the entry of the dorsal root to the cord. There do not appear to be descriptions of FFPs in dogs in the literature, and as their origin in the dog was not investigated here, any conclusions regarding their site of origin remain speculative. The fixed nature of their latency indicates that they are volume conducted potentials arising from events fixed anatomically.

Wiederholt and Iragui-Madoz (1977) using rats, observed four FFPs on the rising slope of P_1. They attributed them in sequence to dorsal

column, dorsal column nucleus and medial lemniscus, ventral posterior thalamic nucleus and sensory radiation and possibly also cerebellar pathways and cerebellum. Using cats allowed a better separation of the FFPs and they were localised to dorsal column, dorsal column nucleus and/or medial lemniscus, cerebellum and/or cerebellar pathways, ventral posterior nucleus of thalamus, sensory radiation and with some thalamic contribution (Iragui-Madoz and Weiderholt, 1977). Human work has produced similar observations but with more complexity, including observation of the peripheral nerve or dorsal root (Cracco and Cracco, 1976; Anziska and Cracco, 1980; Desmedt and Cheron, 1980; Pratt and Star, 1981). Future work may produce more detailed knowledge of these origins, as clearly if up to 11 FFPs can be seen in this study, those smaller numbers reported by other authors may be broken into more separate peaks.

Gasser and Graham (1933) reported cord dorsum potentials following dorsal root stimulation in the same segment which produced a short latency spike compatible with A fibre transmission. This was followed by a large negative potential and a slow positive wave which were labelled intermediary potentials and attributed to internuncial neurons. This distribution was localised and attributed to the ascending and descending branches of the dorsal root nerve which give collaterals to the grey matter. The ascending branch, now smaller continues to the dorsal column nucleus. Barron and Matthews (1938) considered that the slow waves represented local reflex activities and that the spike potentials in the cord were axon volleys whose latency increased with distance from the stimulus. This interpretation has since been modified by Bernhard (1953), Bernhard and Widen (1953), and Gelfan and Tarlov (1955). They suggest that the large negative potential associated with the root entry zones at C_7 and L_4 is post-synaptic and ipsilateral, and represents converging interneuronal activity, some part of which is associated with multisynaptic reflexes taking place in the posterior horn of the grey matter (Lindblom and Ottosson, 1953; Ertekin, 1976). they also observed that the distribution of amplitude of the positive intermediary waves had a rostral skewness around the four or so segments of the root entry zone. Opinion differs as to whether the positive wave is related to reflex activity or to primary afferent depolarisation of propriospinal neurons extending over several segments.

The bipolar records generally showed more axonal volleys than those authors single initial positive and axonal volley. This probably reflects the use of supramaximal stimulation of a distant peripheral nerve allowing time for separation of synchronous volleys in axons of different sizes, and therefore, different conduction velocities. The similarity of their root entry segment potentials recorded from the cord dorsum and these records suggest the these records are basically those which might be recorded from cord dorsum although the activity seen is not necessarily confined to the dorsal columns. Others using similar electrode placings but with monopolar recordings found less complex waveforms than those seen in this study (Nordwall et al. 1979; Holliday et al., 1979).

It was observed that as the recording site moves rostrally, additional peaks separated from those evident around the entry segment. These progressively lost amplitude and increased in latency with a wider separation of peaks as the distance increased. It is assumed that the loss of amplitude is the result of the giving off of collaterals so that neuronal bulk is reduced, and that the apparently different conduction velocities represent axons of different sizes or synaptic activity (Sarnowski et al., 1975). It would be fair to assume that the variation in axonal size is a continuum. Therefore, in order to account for the clear separation of peaks, it must be assumed that different groups of similar sized axons are synchronous and are perhaps grouped by modality, these need not be separated as discrete bundles anatomically. It was not possible to correlate different SEP peaks with cortical FFPs or with a particular anatomical position in the cord but it is presumed that the earlier and larger peaks contribute most to the CEP, and are therefore, mainly in the dorsal column. Certainly the late peaks may be lost in DCS without apparent change in the CEP, and the early peaks must change in order for CEP to change.

In dogs, dorsal column potentials recorded from light touch, hair, joint movement, and deep pressure can also be produced by peripheral electrical stimulation. However, the physical stimuli cannot be detected in the antero lateral column (spinothalamic), although the electrical stimulation produces a response commensurate with $A\beta$ and $A\delta$ fibres.

the so-called "fast-pain fibres" (Illingworth and Molina-Negro, 1974). Shimoji and Kano (1975) recording epidurally in man found that moving from the posterior to the anterior space simply inverted the potentials recorded dorsally which suggests that all cord activity can be observed from the cord dorsum.

Clinical and experimental experience suggests that the use of SEP and CEP has considerable potential in predicting outcome and in monitoring cases of acute cord injury (Nash et al., 1977; Rowed et al., 1978; and Parker, 1978b). In practice it has been found to be a useful method for diagnosing and quantifying the DCS spinal cord lesions in studies of treatment. It remains to be seen how the changes observed would relate temporally to symptomatology in man. It would be impractical to use SEPs in the diagnosis or quantification of DCS. However the technique might have a place in post-treatment follow-up in cases liable to residual damage.

The validity of the evoked potential method was demonstrated by the finding that no major changes in SEPs were seen unless there was severe disruption of blood flow. In practice this meant 'neuron-disabling' blood flows of less than 6 and 15 ml 100 g^{-1} min^{-1} respectively for white and grey matter (Branston et al., 1974, Hallenbeck et al., 1982).

12.2 THE DIVE

The development of the 10 bar (300 ft) dive produced a model of moderate to severe decompression sickness. The systemic upset ranged from mild, which needed little support, to severe enough for about 15 percent to be lost as a result of cardiovascular collapse. Of those 45 dogs included in the final studies only 25 percent required a second dive to produce DCS with cord involvement. The spectrum of evoked potential findings was similar to human clinical experience with occasional occurrences of spontaneous recovery, transient worsening on compression (6 cases) and extensive deterioration after some recovery, to levels worse than before treatment (2 cases). While there is no doubt that most cases were more severely affected than the average human case,

localised unilateral cord involvement was seen with only minor systemic changes. In view of the total unpredictability and inability to dictate the nature of DCS the attrition rate in this model was surprisingly low. Animals were maintained during the surface period with infusions of lactated Ringers solution and bicarbonate. No additional therapy was given.

In the search for the required model of DCS two other useful models were found. Cerebral DCS which is an infrequent diving problem could be studied using the 300 ft dive. Decompression in 5 min produces a useful incidence of cerebral DCS without too frequent overwhelming systemic disturbances. The frequency and severity of cerebral and systemic problems can be controlled by slowing the ascent from 60 ft to take up to 1.5 min. Even at this rate the frequency of cerebral DCS did not fall below 50 percent. It is possible that a change in posture by lowering the dogs heads would further reduce the incidence.

The earlier 230 ft (8 bar) dive produced severe DCS and was probably more akin to 'blow-up' . Certainly that model could not be contained to enable delayed treatment to be studied.

12.3 THE PATHOLOGICAL MECHANISM OF DECOMPRESSION SICKNESS

The most widely accepted explanation of the mechanism of spinal cord DCS is probably the venous obstruction model of Hallenbeck et al. (1975). Hills and James (1982) have argued against it not very convincingly with a proposal of autochthonous bubble formation. While Hennessy (1980) would suggest that all the arguments lie with arterial obstruction. As with most ideas in diving none of these hypotheses is new (Boycott et al, 1908; Haymaker, 1957).

Although the objective in this study was to refine the ideas on treatment, it proved impossible to avoid the issue of the mechanism of cord DCS because of the conflicting observations.

At all phases in the study the same conflicts were seen. The control of the animal model was continually refined so that at each

phase the insult was less severe. For instance in the last two phases cerebral DCS fell from 72 to 50 percent and the frequency of CSF pressure rise, fell from 92 to 65 percent.

In general the systemic changes were in keeping with the venous obstruction model. There was a high incidence of raised CSF pressure compatible with EVVS obstruction which preceded by varying intervals, changes in SEPs indicating cord DCS. Increases in RVP were also frequent at about 66 percent in both groups. However, there were 9 cases where CSF pressure did not increase although cord lesions did develop. This is theoretically possible with a very localised EVVS obstruction and associated intramedullary circulatory block. However, there can have been no gross venous obstruction. Hallenbeck et al. (1975, 1976, 1978) repeatedly report that at no time did they observe any evidence of cerebral DCS. However even in the final study reported here there was a 50 percent incidence. This cannot be entirely attributed to posture but must in part be attributed to the nature of the DCS arising from two different dive models.

The blood flow studies produced additional conflicting findings. Hallenbeck and Sokoloff (1978) observed that the cords in paretic dogs usually had uniformly low flows of less than 5 ml 100 g^{-1} min^{-1} in affected segments. They did not observe the unilateral disruption seen in 86J and 86P (Fig. 19). They argued that the uniformity was the result of bilateral epidural vertebral venous obstruction, stating that "mottled" unilateral changes would need to be seen to support the possibility that the cord ischaemia was due to circulating arterial gas bubbles. These results therefore raise that possibility, particularly when seen in association with discrete brain lesions (86J). The EEG attenuation and foci of autoradiographic flow impairment in the brain indicate the probability of circulating arterial bubbles in several animals. Nevertheless, the observed unilateral cord ischaemia is also compatible with subsequent local events such as increasing vascular resistance and autochthonous bubble formation accompanying unilateral epidural vein obstruction, as noted previously (Hallenbeck, 1976).

There is little doubt that intravascular gas was present. The flow studies demonstrated vascular obstruction and of the 45 dogs in the

final studies 35 showed a transient fall of blood pressure immediately on compression. This is very suggestive of intravascular gas causing increased peripheral resistance. No ready explanation is available for the 6 cases of deterioration occurring during compression. There was no particular association with pure or even a high PO_2. The cases were randomly distributed. Transient vessel collapse on compressed bubbles might reduce blood supply.

Venous obstruction cannot be applied as an explanation of cerebral DCS. This must be either arterial in origin or the result of autochthonous bubble formation. In seven dogs in the last two studies there was a rise in RVP before or coincident with the fall in EEG amplitude. Such a rise in RVP with the associated respiratory acidosis and hypoxaemia indicates pulmonary vascular bubble overload and the probability of bubble break-through leading to arterial gas embolism (Butler and Hills, 1979). There remain 21 other dogs with EEG losses which were generally the first signs of DCS. There is therefore a strong possibility that autochthonous bubble formation could be the mechanism in these cases.

The distribution of haemorrhages in the cords of 9 dogs with DCS showed partial grey matter sparing in only 8 out of 34 cord segments showing any degree of haemorrhage (Table 34). Grey matter sparing is said to be compatible with venous obstruction while arterial occlusion affects grey matter particularly in the watershed regions (Henson and Parsons, 1967). The cord sections presented a picture apparently dominated by evidence of arterial obstruction with haemorrhages concentrated in grey matter. However this presentation is also compatible with general hypoxaemia.

Although systemically the presentation of DCS did not conflict with the venous obstruction model of Hallenbeck et al. (1975), the frequency of cerebral involvement and the dominance of cord grey matter haemorrhages and unilateral SEP loss in 9 dogs is at variance with that model. This reinforces the probability that arterial and autochthonous bubble formation have more than an incidental role in the pathology of cord DCS in this model. Crockett et al. (1979) reported examples both with and without grey matter sparing. Palmer

et al. (1978) saw extensive grey matter haemorrhages associated with white matter infarction in goat cords. The question then arises as to whether the different microscopic appearances represent cord DCS arising from different dive profiles and therefore of different severities.

Although a large number of clinical cases of cord DCS have been reported few have been documented with even moderate systemic disturbances (Barnard et al., 1966; Brunner et al., 1964; Moretti et al., 1973; Rivera, 1964; Saumarez et al., 1973; Slark, 1965; Van der Aue et al., 1947). What human evidence exists for venous obstruction is based on morbid pathology (Bauer, 1870; Hayashi, et al., 1978; Kitano et al., 1977). Other animal work has similarly resulted in near moribund cases (Walkiewiecz et al., 1979). This lends support to the idea that particular dive profiles may produce a particular form of pathology. It would appear that the 10 bar dive for 15 min produces a full spectrum of pathology.

12.4 FACTORS IN RECOVERY

Outside the factors of oxygen and pressure in treatment there are undoubtedly uncontrolled factors related to the pathology which influence the extent of recovery. There was no relationship between the amplitude loss of the controlling SEP and the amount recovered. There was also no relationship between the amount of SEP loss and the number of cord divisions affected. The only clear relationship indicated that earlier SEP loss led to less chance of recovery. This experimentally corroborated Rivera's (1963) observations that early onset led to more residua. However there was no connection between onset time and amount of SEP loss. There did not appear to be any connection between the severity of systemic disturbance and recovery. This latter observation probably arises from the efforts made to combat systemic changes and the exclusion of those dogs which failed to meet the inclusion criteria.

To simplify the discussion pure ischaemia will be considered first. Cord and CNS survival has been studied using basically three techniques; global and local ischaemia broadly as described earlier,

interruption of blood supply by vessel clamping or by bleeding and hypotension, and by asphyxia and anoxia. The effects of these insults after restoration of blood flow or oxygenation have been followed using blood flow studies, pathology, electrical function and clinical recovery.

Cord neuronal survival has been investigated in a setting of global or local ischaemia produced by raising CSF pressure. This method by emptying the neuraxis of blood appears to provide some protection against secondary deterioration resulting from blood-damaged tissue interaction (Hallenbeck, 1977). Neely and Youmans (1963) found some degree of neuronal recovery following 25 min of ischaemia, while Wolfe (1960) found a 100% mortality in animals subjected to only 5 min of circulatory arrest where the neuraxis blood was left in situ. Similarly, Van Harrevald and Marmont (1939) found some survival and functional recovery following not more than 25 min of localised cord pressure ischaemia ("bloodless ischaemia"). Longer periods produced less recovery.

The relative vulnerability of the cord components has mostly been observed in experiments with vessel clamping or hypotension, and has been shown to be related to their capacity to recovery from anoxia. Whatever the cause of the insult to the cord, the overall findings are similar both in type and in timing, although asphyxia tends to produce later effects (Gelfan and Tarlov, 1955).

The local events are the earliest to be affected, with a facilitation of reflex related local potentials in the SEP and of reflexes within the first minute (Bernhard and Koll, 1953; Brooks and Eccles, 1947; Gelflan and Tarlov, 1955; Porter et al., 1938). These may reflect a loss of inhibitory activity. Thereafter, by 3 to 5 min, the reflexes and segmental negative and positive SEP waves have disappeared (Wang, 1959).

Prolonging the insult progressively reduces the amplitude of the travelling SEP waves, the intramedullary primary afferents, until no activity is detectable by 8 to 20 min (Cracco and Evans, 1978; Gelfan and Tarlov, 1955, 1956; Kobrine et al., 1979, 1980). Motoneurons cease

to function within 2 min of ischaemia or 3 to 5 min of asphyxia; interneurons and afferent long tract fibres last about 1.5 and 2.5 times as long respectively (Gelfan and Tarlov, 1956).

Removal of the insult within 5 min of the onset of the electrical silence of the component will generally restore much of its function (Brookes and Eccles, 1947; Kobrine et al., 1979, 1980). In terms of overall ischaemia or asphyxia, a duration of the insult in excess of 15 min appears to result in some permanent loss of function and detectable microscopic pathology (Gelfan and Tarlov, 1955, Tureen, 1936; Van Harreveld and Marmont, 1939). Restoration of blood flow or oxygen after 4 to 15 min of absence seems to restore function completely without permanent pathology, at a rate directly related to the duration of the insult (Bernhard and Koll, 1953; Brookes and Eccles, 1947; Gelfan and Tarlov, 1955; Tureen, 1936). The most rapid recovery is in the large long tract neurons (Gelfan and Tarlov, 1955).

It is now well established for cerebral blood flow that there is a threshold of blood flow below which function ceases, the "ischaemic penumbra" of "neuron-disabling" flow (Astrup et al., 1981), but where increasing the flow will rapidly restore function (Branston et al., 1974). It can therefore be assumed that some cord DCS is the result not of complete microcirculatory arrest but of marginally adequate perfusion. In view of the now defined survival limits of cord tissue in total ischaemia, reduced blood flow remains the only alternative explanation, besides the existance of the smallest discrete areas of vascular obstruction, for the possibility of any degree of recovery of function after long delays before treatment. A current unknown is how long can "neuron-disabling" flows exist before the neurons become irretrievably damaged or flow ceases altogether as a result of the haematological events triggered by DCS? If neuron survival is prolonged then all cases, no matter what delays occur, should be treated.

From the pathology the only indication of factors related to recovery were that those with least haemorrhage tended to do better than those with most. However the numbers were too few to be sure that there was no association between onset time and numbers of

haemorrhages. There was no correlation between frequency of haemorrhage and previous hypertension. Discussion must come down to speculation about events at a cellular level such as autochthonous bubble formation. There is a lag time of about 5 min between onset of ischaemia and loss of SEP, but tissue compression as might be caused by autochthonous bubbleformation would cause sudden SEP loss. In view of the number of dogs in which such an event may have occurred in the brain this becomes a strong possibility in the cord. In fact in the last two studies, three dogs showed an SEP loss within 4 min of surfacing. This might indicate autochthonous bubbles. The question of the relative damage caused by autochthonous bubbles versus vascular obstruction arises. If haemorrhage does not occur with vascular obstruction then integrity is probably preserved. Recovery then becomes a matter of the duration and degree of ischaemia.

Intuitively it seems likely that autochthonous bubbles formation in neural tissues must disrupt neural integrity. If it damages cells or axons then recovery is unlikely. However if the damage was confined to myelin then the possibility of repairable damage might exist. Such a propostion would allow for some of the long delayed recovery now largely attributed to adaptation. Clearly severe myelin disruption would damage axons thus causing permanent loss.

If vascular obstruction is a major mechanism in cord DCS then a high perfusion pressure should be beneficial in treatment. However in the normal cord, blood flow is constant within a range of mean blood pressure of 45 to 135 mm Hg (Sandler and Tator, 1976). Precisely how this affects fo cally damaged cord remains unclear. In stroke it is believed that hypotension should be avoided in order to maintain perfusion in the marginal areas (Astrup et al., 1981). Any influence of blood pressure on recovery was removed. However the secondary effect of haematocrit was not entirely eliminated during the oxygen study.

In these studies the absolute level of recovery may have been enhanced by the use of pentobarbital anaesthesia. This suppresses neural metabolism so reducing oxygen demand (Feuslet et al., 1981;

Astrup et al., 1981). As this was common to all treatments it cannot be considered to have influenced the outcome of the experiment.

12.5 TREATMENT WITH OXYGEN AND PRESSURE

Having demonstrated a difference in efficacy for a range of oxygen partial pressures all at the same absolute pressure, it is necessary to attribute the difference to some property of the oxygen. As there were few systemic differences between the groups only the nature of SEP recovery remains. The acute response to treatment suggested an optimum treatment of 2.0 bar PO_2. Pressure was beneficial but a PO_2 between 1.0 and 1.5 bar did not produce much additional recovery, 1 and 2 dogs respectively showed further notable recovery with those treatments. The initial poor response could be attributable to inadequate tissue oxygenation because physically all groups received the same compression. In addition inert gas clearance would be slower in the low oxygen groups. These two factors could lead to a longer early hypoxic period which would lead to further cell death thus reducing longer term recovery.

At the higher PO_2 of 2.5 and 3.0 bar there would be vasoconstriction (Torbati et al., 1979) even in the damaged tissue (Ledingham, 1977). While the increased inert gas gradient would hasten the clearance of bubbles, the vasoconstriction with reduced flow would retard bubble clearance and restoration of flow. The extended capacity for oxygen diffusion which probably meets the greatest need (Astrup, et al. 1981) would preserve hypoxic tissues for sometime enabling them to recover later when perfusion was restored. However the vasoconstriction could reduce the oxygen supply. Certainly 5 and 4 dogs respectively showed further improvement during treatments.

Other factors play a part in secondary deterioration. Arterial air emboli cause endothelial damage in less than 3 min with resultant fluid and macromolecule leakage causing vasogenic oedema (Vise et al., 1978). If the surrounding tissue has been ischaemic sufficiently long then cytotoxic oedema will also develop. When flow is restored within 60 min cytotoxic oedema lessens only to be replaced by vasogenic oedema (Ito et al., 1979). The variable deterioration between cases

may reflect such factors as the amount of intravascular gas and possibly the duration of its presence.

Other possibilities are the development of secondary post-ischaemic microcirculatory impairment, and the 'no-reflow' phenomenon. These arise from blood-damaged tissue interaction (Hallenbeck et al., 1982). There are also the products of blood-bubble interactions (Philp et al., 1972). Flow is initially restored but is then reduced as a form of local coagulopathy develops (Hallenbeck et al., 1982).

Either of these mechanisms may have caused the secondary deterioration, which exceeded what would have been caused by time alone in the model. The only indication that any of the treatments had a better preventive action than any other is that the 5 dogs which did not deteriorate noteably were breathing 2.0 or more bar of oxygen. The main advantages of 2.0 to 2.5 bar of oxygen in treating spinal cord DCS appear to have been effective in the early stages of treatment. This implies that tissue oxygenation is probably the mainstay of oxygen therapy in the initial treatment of DCS. However if all the dogs treated with a PO_2 of 2.0 bar or more, are compared with those treated with a lower PO_2 for the frequency of no significant secondary deterioration (< 5%). It is seen that there were 15 out of 35 dogs treated with higher oxygen and none out of 10 in the lower oxygen groups.

Buckles (1968) observed that as DCS developed in hamsters small bubbles coalesced as they arrived, first in the arteries and then in the veins. Bubbles appearing in the veins also travelled distally filling from large vessels. For arterial bubbles to enter arterioles required an adequate perfusion pressure. Small bubbles became sausage shaped as they coalesced. Film of bubbles in larger vessels showed that they tended to remain spherical (Hallenbeck, 1976). Interstitial bubbles would be unable to coalesce and would probably be distorted by structures. However for practical purposes they may be considered spherical. Compression caused arterial bubbles to move distally and to break up while venous bubbles moved proximally and broke up (Buckles, 1968). Some bubbles remained adherent to the vessel wall and shrunk until they were reabsorbed in situ. Both

venous and arterial bubbles were seen to be circulating for up to 10 min after recompression.

The use of Boyles Law to determine what would be an appropriate treatment pressure founders on not knowing the nature and location of the offending bubbles. In lozenge shaped bubbles volume must be reduced before reduction in diameter can occur as it does in spherical bubbles.

Compression to 3 bar reduces surface volume to 33 percent and diameter to 69 percent. At 5 bar this is 20 percent and 58 percent respectively and at 7 bar it is 14 percent and 52 percent. Evidently the law of diminishing returns becomes relevant for diameter before it does so for volume. Volume is dramatically reduced by moderate compression but it takes much greater pressures to similarly reduce diameter.

Kunkle and Beckman (1983) in discussing bubble resolution conclude that because of the increased inert gas tension inherent in breathing air at 6 bar, the enhanced reduction in bubble size is countered by the reduced rate of gas clearance. This results in a smaller rate of bubble clearance to that found while breathing oxygen at 2.8 bar. The advantage of greater pressures is supposed to be the rapid initial reduction in bubble size for the early restoration of circulation.

The objectives in treatment are to stop further bubble growth, restore oxygenation and circulation, and to increase inert gas clearance. It is axiomatic that compression and a raised PO_2 are necesary to achieve these aims. It has now been established that an optimal PO_2 is about 2.0 bar. This has the advantage of being less toxic than the currently used PO_2 of 2.8 bar. The degree of vasoconstriction will be less which must be advantageous and it can be breathed for longer periods without break. No effort has been made to establish a pressure threshold in these studies but it has been shown that pressures above 3 bar do not improve recovery in this model. This conforms with the findings of Barnard and Hanson (1973) and Leitch, et al. (1984a).

A major remaining question is whether a failure of recovery at a lower pressure can be reversed by further compression. In view of the probable difference in pathology it seems unlikely. Certainly there is little clinical evidence that further compression produces a step improvement. It would take a difficult experiment to try and test that hypothesis.

The disadvantages of breathing mixtures which include nitrogen is that the nitrogen gradient is reduced. However breathing 34% nitrogen at 3 bar only gives a PN_2 of 1.02 bar; little more than breathing room air at atmospheric pressure. In practice using 66% oxygen at 3 bar does not appear to have any disadvantages when compared with 2.8 bar of oxygen inspite of the additional nitrogen. Although the outcome was the same the rate of recovery at the higher pressure with the lower oxygen may be better. The reduction in risk from oxygen toxicity would be the main reason to move away from the 2.8 bar oxygen treatment. The possibility of an increased rate of response would also be a sound reason. A new treatment would take the form of breathing 66 percent oxygen at 20 m (66 ft) for one or two hours with a 10 min air break per hour followed by a bleed to 10 m (33 ft) and a switch to oxygen and then complete a table similar to RN 62 (USN 6).

This model of spinal cord DCS now lends itself to testing chemotherapy and also some of the more contentious treatment ploys being suggested such as oxyhelium for treating air DCS.

12.6 DELAYED RECOVERY

Nine out of 35 dogs treated with oxygen at 2.0 bar or more continued to improve throughout treatment. This was similar to clinical experience. The maximum survivable period of ischaemia for cord tissue is probably about 15 to 20 min. Successful late treatments suggest that the cord was not totally ischaemic but was in the 'ischaemic penumbra'. Transient recovery may indicate that oxygenation is sufficiently improved to restore function but that small reductions in perfusion or oxygen can revert tissue to a non-

functioning state. This'ischaemic penumbra' is the only rational explanation for any response to compression in cases treated after delays of days. In the success of repetitive therapies this would also apply, but it is possible that non-functioning tissue might need a greater than usual PO_2 to restore function, a sort of physiological 'kick start'.

When late and prolonged recovery of function occurs after cessation of pressure and oxygen treatment it must be assumed that it is compensatory adjustment of remaining function, with activation of normally redundant alternate sensory pathways and satellite innervation of muscle fibres and not recovery of function (Brenowitz and Pubols, 1981; De la Torre, 1981). Only when pressure and oxygen are seen to have an effect is it possible to say that there is any chance of recovery of function.

SECTION 13

SUMMARY AND CONCLUSIONS

SUMMARY AND CONCLUSIONS

1. Spinal and cortical somotosensory evoked potentials have been reproducibly recorded over periods of up to 5 hours. They were recorded from multiple inputs and recording sites. Simultaneous recording from 3 cord sites and the cortex allowed interrogation of gross cord segments.

2. It was demonstrated that while increasing air pressure caused a progressive attenuation of the CEPs, the SEPs were not significantly affected. Helium at the same pressures had no attenuating effect.

3. It proved possible to diagnose and even apply numerical values to spinal cord DCS using this model. It was demonstrated that in a syndrome considered to be largely the result of vascular obstruction, SEPs do not materially alter without clear changes in spinal cord blood flows.

4. The provoking dive of 10 bar for 15 minutes produced a full spectrum of systemic presentations of DCS and of cord pathology. There was a commonality with clinical experience although the results were clearly at the severe end of clinical experience with frequent cerebral involvement.

5. The presentation of DCS generally tended to support the venous obstruction mechanism of cord DCS. However the frequency of cerebral DCS, cord grey matter haemorrhage, and very early onset of SEP changes, suggest that autochthonous bubble formation and arterial gas may have more than an incidental role in the pathology of cord DCS.

6. It was confirmed that total cord ischaemia lasting more than 15 minutes is likely to result in only partial recovery of function after restoration of blood flow. Once past 15 minutes the duration of ischaemia is directly related to the amount of permanently lost function. As there was about a 4 minute delay

between onset of ischaemia and detection of SEP changes, 15 minutes was selected as the post diagnosis interval before starting treatment in order to study the delayed treatment of cord DCS. This proved to be an appropriate interval as few dogs achieved full recovery at any time.

7. There was a strong association between poor recovery during treatment and early onset of cord DCS. This, in association with a tendency for poor recovery to be associated with extensive haemorrhage in other dogs, suggested that mechanical tissue damage might be the problem. This lends support to the possibility that early onset might be the result of autochthonous bubble formation which with its tissue disruption would militate against recovery. Clinical experience tends to support this observation.

8. In the more serious cases loss of plasma volume was a major problem. There was a tendency for cases where haematocrit was not adequately controlled to do less well than those with lower haematocrits.

9. During treatment most recovery occurred by 15 minutes and group mean recoveries tended to peak at about 60 minutes. Secondary deterioration was common in all treatment groups. The only cases to show minimal or no deterioration occurred in those groups with 2.0 bar or more of oxygen.

10. Electrocardiographic changes were seen in 27 percent of cases of DCS. At the end of 2 hours of compression therapy 30 percent had still not returned to the control condition. This suggests that in clinical practice moreattention should be paid to ECG recording than is presently the case.

11. There is no indication that once a pressure threshold is exceeded, the high levels of oxygen currently favoured for treatment are better than lower oxygen levels. The lowest but at least equally effective PO_2 was found to be the 2.0 bar.

12. With the established optimum PO_2, there is no indication that raising pressure beyond a threshold of the order of 3.0 bar in any way improves SEP recovery.

13. The major outstanding question is whether cases which fail to respond within 15 minutes at a lower pressure will improve if taken to greater pressures. As it begins to appear that such cases may be the result more of mechanical damage from autochthonous bubbles or from haemorrhage than of ischaemia, it is likely that the answer will be no. It might be possible, though difficult, to test this hypothesis with this model.

14. The anaesthetised dog model using evoked potentials to study the treatment of spinal cord DCS has proved effective. It can go on to test the use of helium or drugs to try and improve recovery. It is probable that early recovery will not be altered but that secondary deterioration might be reduced by drugs. How valid extrapolation from this model to clinical experience would be is unknown. It can only be said that the course of DCS and recovery often mimicked the author's clinical experience.

15. A new approach to treatment is proposed. It would be one to two hours of 66 percent oxygen at 3 bar (20 m) followed by the same duration of pure oxygen breathing at 2 bar (10 m). The last 10 minutes of each hour would be spent breathing air. The transit times between each stage would take 30 min. The form is not much different from the current treatments RN 62 (USN 6). The outcome with this new approach may not be any different from current treatment. However the greatly reduced risk of oxygen toxicity has much to recommend it. The presence of nitrogen in the treatment mixtures is probably of limited significance and would be well offset by the oxygen breathing at 10 m. Such a protocol could be tested by doing a surface decompression dive and doubling the surface interval before starting treatment. The only logistic problem is that 66 percent oxygen is not a standard mixture.

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APPENDIX A

INDIVIDUAL DATA - OXYGEN STUDY

TABLE

A1 - Spinal Evoked Potentials - Primary Lesion

A2 - General Descriptive Data

A3 - Monitored Physiological Variables

A4 - Arterial Blood Analysis

- 1 PO_2 1.0 bar
- 2 PO_2 1.5 bar
- 3 PO_2 2.0 bar
- 4 PO_2 2.5 bar
- 5 PO_2 3.0 bar

SYMBOLS AND UNITS

LP-L	Left peroneal to lumbar SEP
RP-L	Right peroneal to lumbar SEP
$LM/_P$-C	Left median to cervical SEP. Change first seen with peroneal SEP
RP-T	Right peroneal to thoracic SEP
*	SEP recorded at pressure
[ ]	Further SEP loss on compression
D	Diagnosis of cord DCS
℞	Treatment
Time	min
Weight	kg

Pressures/Tensions - mm Hg

Fluid volume - ml

TABLE A1-1

TREATMENT WITH PO_2 1.0 BAR AT 50 BAR

SPINAL EVOKED POTENTIAL - PRIMARY LESION

DOG	140	141	142	143	144
SEP RECORD	LP-L	LP-L	LP-L	LP-L	RP-L
EVOKED POTENTIAL AS PERCENT OF CONTROL					
Pre-Pre-Diagnosis	111.3	96.6	96.0*	103.9	99.3
Pre-Diagnosis	105.9	92.0	104.4	101.0	97.6
Diagnosis (D)	65.5	78.3	89.3	84.0	64.9
Pre-Bx	20.9	71.9	7.9	25.1	[38.2]
Bx - 15 min	41.2	92.8	23.0	79.8	50.4
Bx - 40 min	31.7	79.5	20.0	76.1	52.7
Bx - 80 min	31.7	65.8	20.6	82.4	64.5
Bx - 120 min	30.7	35.0	18.6	67.8	56.9
LOSS OF SEP AND RECOVERY					
% Lost	79.1	28.1	92.1	74.9	61.8
% Recovered @ 15	20.3	20.9	15.1	54.7	12.2
40	10.8	7.6	12.1	51.0	14.5
80	10.8	-6.1	12.7	57.3	26.3
120	9.8	-36.9	10.7	42.7	18.7
RATIO OF RECOVERY TO LOSS AS A PERCENT					
15 min	25.7	74.4	16.4	73.0	19.7
40 min	13.6	27.0	13.1	68.1	23.5
80 min	13.6	0	13.8	76.5	42.6
120 min	12.4	0	11.6	57.0	30.3
ABSOLUTE CHANGE					
Pre-Pre-D to Pre-D	-5.4	-4.6	+8.4	-2.9	-1.7
Pre-D to D	-40.4	-13.7	-15.1	-17.0	-32.7
D to Pre-Bx	-44.6	-6.4	-81.4	-58.9	-27.6
Loss over compression	0	0	0	0	-31.3
TIME INTERVALS (Min)					
From Surface to D	9	10	6	13	24
Pre-D to D	4	5	5	2	4
D to Bx	15	15	17	15	15
Last SEP to Bx	0	8	4	0	0

TABLE A1-2

TREATMENT WITH PO_2 1.5 BAR AT 5.0 BAR

SPINAL EVOKED POTENTIAL - PRIMARY LESION

DOG	150	151	152	153	154
SEP RECORD	LP-L	LP-L	RP-L	[LM/$_P$-C]	[LM/$_P$-C]
EVOKED POTENTIAL AS PERCENT OF CONTROL					
Pre-Pre-Diagnosis	110.7	101.8*	108.4*	97.2*	98.6*
Pre-Diagnosis	106.7	97.0	104.0	108.6	89.2
Diagnosis (D)	107.8	86.0	88.6	15.9	79.6
Pre-Bx	82.0	39.4	70.5	11.2	36.6
Bx 15 min	99.9	48.1	86.1	41.2	83.0
Bx 40 min	81.3	63.1	77.1	47.6	75.1
Bx 80 min	81.7	69.4	73.6	38.8	73.8
Bx 120 min	88.5	63.9	69.2	40.8	75.9
LOSS OF SEP AND RECOVERY					
% Lost	18.0	60.6	29.5	88.8	63.4
% Recovered @ 15	17.9	8.7	15.6	30.0	46.4
40	-0.7	23.7	6.6	36.4	38.5
80	-0.3	30.0	3.1	27.6	37.2
120	6.5	24.5	-1.3	29.6	39.3
RATIO OF RECOVERY TO LOSS AS A PERCENT					
15 min	99.4	14.4	52.9	33.8	73.2
40 min	0	39.1	22.4	41.0	60.7
80 min	0	49.5	10.5	31.1	58.7
120 min	36.0	40.4	0	33.3	62.0
ABSOLUTE CHANGE					
Pre-pre-D to Pre-D	-4.0	-4.8	-4.4	+10.8	-4.7
Pre-D to D	+1.1	-11.0	-15.4	-20.7	-9.6
D to Pre-Bx	-25.8	-46.6	-18.1	-4.7	-43.0
Loss over compression	0	0	0	0	0
TIME INTERVALS (Min)					
From Surface to D	18	7	13	25	12
Pre-D to D	3	5	5	7	8
D to Bx	15	15	15	17	15
Last SEP to Bx	0	0	3	2	2

TABLE A1-3

TREATMENT WITH PO_2 2.0 BAR AT 5.0 BAR

SPINAL EVOKED POTENTIAL - PRIMARY LESION

DOG	160	161	162	163	164
SEP RECORD	LP-L	RP-L	RP-L	LP-L	LP-L
EVOKED POTENTIAL AS PERCENT OF CONTROL					
Pre-Pre-Diagnosis	93.0	97.5	96.4	110.8	101.3
Pre-Diagnosis	94.2	92.4	119.7	103.6	103.4
Diagnosis (D)	40.9	47.0	117.5	65.5	67.2
Pre-℞	27.8	29.1	51.1	0	45.6
℞ 15 min	90.1	68.8	100.0	39.1	83.7
℞ 40 min	98.0	64.7	98.5	65.5	90.9
℞ 80 min	76.3	61.4	83.9	75.7	91.2
℞ 120 min	77.6	53.1	81.0	77.7	104.9
LOSS OF SEP AND RECOVERY					
% Lost	72.2	70.9	48.9	100.0	54.4
% Recovered @ 15	62.3	39.7	48.9	39.1	38.1
40	70.2	35.6	47.4	65.5	45.3
80	48.5	32.3	32.8	75.7	45.6
120	49.8	24.0	29.9	77.7	59.3
RATIO OF RECOVERY TO LOSS AS A PERCENT					
15 min	86.3	56.0	100.0	39.1	70.0
40 min	97.2	50.2	96.9	65.5	83.3
80 min	67.2	45.6	67.1	75.7	83.8
120 min	69.0	33.8	61.1	77.7	109.0
ABSOLUTE CHANGE					
Pre-Pre-D to Pre-D	+1.2	-5.1	+23.3	-7.2	+1.9
Pre-D to D	-53.3	+4.6	-2.2	-38.1	-36.2
D to Pre-℞	-13.1	-67.9	-66.4	-65.5	-21.6
Loss over compression	0	0	0	0	0
TIME INTERVALS(Min)					
From Surface to D	19	14	20	22	24
Pre-D to D	7	5	6	5	4
D to ℞	15	18	15	15.5	15
Last SEP to ℞	1	5	0	1	1

TABLE A1-4

TREATMENT WITH PO_2 2.5 BAR AT 5.0 BAR

SPINAL EVOKED POTENTIAL - PRIMARY LESION

DOG	170	171	172	173	174
SEP RECORD	RP-T	LP-L	LP-L	LP-L	LP-L
EVOKED POTENTIAL AS PERCENT OF CONTROL					
Pre-Pre-Diagnosis	100.0*	94.4	84.5	109.3	97.6
Pre-Diagnosis	100.0	88.4	92.8	106.7	101.3
Diagnosis(D)	96.1	28.4	81.8	66.7	91.6
Pre-Br	16.9	0	8.6	46.7	85.4
Br 15 min	71.4	27.6	43.5	94.7	91.1
Br 40 min	89.6	31.9	56.2	100.0	96.2
Br 80 min	88.3	31.0	62.8	94.7	98.1
Br 120 min	63.6	23.0	63.8	92.0	100.5
LOSS OF SEP AND RECOVERY					
% Lost	83.1	100.0	91.4	53.3	14.6
% Recovered @ 15	54.5	27.6	34.9	48.0	5.7
40	72.7	31.9	47.6	53.3	10.8
80	71.4	31.0	54.2	48.0	12.7
120	46.7	23.0	55.2	45.3	15.1
RATIO OF RECOVERY TO LOSS AS A PERCENT					
15 min	65.6	27.6	38.2	90.1	39.0
40 min	87.5	31.9	52.1	100.0	74.0
80 min	85.9	31.0	59.3	90.1	87.0
120 min	56.2	23.0	60.4	85.0	103.4
ABSOLUTE CHANGE					
Pre-Pre-D to Pre-D	0	-6.0	+8.3	-2.6	+3.7
Pre-D to D	-3.9	-60.0	-11.0	-40.0	-9.7
D to Pre-Br	-79.2	-28.4	-73.2	-20.0	-6.2
Loss over compression	0	0	0	0	0
TIME INTERVALS (Min)					
From Surface to D	20	21	20	25	10
Pre-D to D	20	5	4	5	5
D to Br	14	15	16.5	17	15
Last SEP to Br	2	5	5	1	0

TABLE A1-5

TREATMENT WITH PO_2 3.0 BAR AT 5.0 BAR

SPINAL EVOKED POTENTIAL - PRIMARY LESION

DOG	180	181	182	183	184
SEP RECORD	LP-L	RP-L	LP-L	LP-L	RP-L
EVOKED POTENTIAL AS PERCENT OF CONTROL					
Pre-Pre-Diagnosis	94.7	100.0*	100.7	85.2	100.0*
Pre-Diagnosis	82.9	100.0	101·8	95.3	91.4
Diagnosis (D)	70.9	77.4	80.1	69.8	69.5
Pre-℞	42.4	23.0	55.5	0	[2.5]
℞ 15 min	70.9	77.4	80.1	38.3	7.9
℞ 40 min	70.9	87.1	85.2	57.7	8.4
℞ 80 min	76.1	58.5	74.0	39.6	10.9
℞ 120 min	71.4	62.7	79.9	40.9	14.4
LOSS OF SEP AND RECOVERY					
% Lost	57.6	77.0	44.5	100.0	97.5
% Recovered @ 15	28.5	54.4	24.6	38.3	5.4
40	28.5	64.1	29.7	57.7	5.9
80	33.7	35.5	18.5	39.6	8.4
120	29.0	39.7	24.4	40.9	11.9
RATIO OR RECOVERY TO LOSS AS A PERCENT					
15 min	49.5	70.6	55.3	38.3	5.5
40 min	49.5	83.2	66.7	57.7	6.0
80 min	58.5	46.1	41.6	39.6	8.6
120 min	50.3	51.6	54.8	40.9	12.2
ABSOLUTE CHANGE					
Pre-Pre-D to Pre-D	-11.8	0	+1.1	+10.1	-8.6
Pre-D to D	-12.0	-22.6	-21.7	-25.5	-21.9
D to Pre ℞	-28.5	-54.4	-24.6	-69.8	-67.0
Loss over compression	0	0	0	0	-7.9
TIME INTERVALS (min)					
From Surface to D	21	9	13	17	4
Pre-D to D	2	9	6	5	4
D to ℞	17	14	17	15	15
Last SEP to ℞	1	4	3	1	7

TABLE A2-1

TREATMENT WITH PO_2 1.0 BAR AT 5.0 BAR

GENERAL DESCRIPTIVE DATA

DOG	140	141	142	143	144
Weight (kg)	11.8	13.2	10.3	10.9	10.0
Bottom Time (min)	12	15	15	15	15
Ascent time	5.3	5.4	5.3	5.0	5.0
2nd Bottom time	-	10	-	13	-
2nd Ascent time	-	5.6	-	5.0	-
RVP ↑ Time	4	6	6	14	13
CSFP ↑ Time	9	6	1	1	3
EEG ↓ Time	-	1	4	1	3
CEP ↓ Time	9	1	6	11	3
SEP ↓ Time	9	10	6	13	24
ECG Δ Time	-	-	-	5	✓
$\overline{BP}$ ↑ Time	-	12	10	-	-
$\overline{BP}$ ↓ Time	-	-	-	-	-
$\overline{BP}$ Δ on compression (mm Hg)	-20	-25	-15	-35	-35
Fluid Balance(ml)	+265	+420	+285	+210	+125
Pre-℞ Fluid	40	100	170	355	110
℞ Fluid	400	470	190	0	90
Fluid Out	185	150	75	145	75

TABLE A2-2

TREATMENT WITH PO_2 1.5 BAR AT 5.0 BAR

GENERAL DESCRIPTIVE DATA

DOG	150	151	152	153	154
Weight	10.0	13.6	10.9	9.1	11.8
Bottom Time	12	15	15	15	15
Ascent Time	5.5	5.7	5.0	5.3	5.0
2nd Bottom Time	-	10	-	-	12
2nd Ascent Time	-	5.6	-	-	5.0
RVP↑ Time	16	6	?	4	8
CSFP↑	16	6	2	1	6
EEG↓	-	3	4	1	6
CEP↓	22	7	5	1	6
SEP↓	17	7	13	25	14
ECGΔ	-	3	21	-	6
$\overline{BP}$ ↑	24	-	14	14	6
$\overline{BP}$ ↓	-	3	-	34	-
$\overline{BP}$Δon com-	-5	-15	-40	+10	-40
Fluid Balance	+200	-35	+130	+275	+450
Pre-℞ Fluid	80	95	60	402	100
℞ Fluid	300	300	180	0	480
Fluid Out	180	430	110	125	130

TABLE A2-3

TREATMENT WITH PO_2 2.0 BAR AT 5.0 BAR

GENERAL DESCRIPTIVE DATA

DOG	160	161	162	163	164
Weight	13.6	12.7	13.6	11.3	11.8
Bottom Time	14	15	15	15	15
Ascent Time	5.6	5.0	6.0	5.3	5.0
2nd Bottom Time	-	-	12	12	-
2nd Ascent Time	-	-	5.0	5.0	-
RVP↑ Time	-	13	16	-	6
CSFP↑	?	13	6	7	6
EEG↓	-	-	16	7	11
CEP↓	16	18	20	7	11
SEP↓	16	14	20	22	24
ECG Δ	-	-	-	✓	✓
$\overline{BP}$ ↑	-	-	-	-	-
$\overline{BP}$ ↓	-	-	-	-	-
$\overline{BP}$ Δ on com-	-5	-25	-20	-10	0
Fluid Blance	+65	+295	+40	-45	+115
Pre-℞ Fluid	60	100	40	110	30
℞ Fluid	180	295	250	70	185
Fluid Out	175	100	250	225	100

TABLE A2-4

TREATMENT WITH PO_2 2.5 BAR AT 5.0 BAR

GENERAL DESCRIPTIVE DATA

DOG	170	171	172	173	174
Weight	13.6	10.9	10.7	10.4	12.3
Bottom Time	12	15	15	15	15
Ascent Time	5.0	5.7	5.4	5.0	5.0
2nd Bottom Time	-	-	-	-	-
2nd Ascent Time	-	-	-	-	-
RVP↑ Time	8	-	-	-	2
CSFP↑	3	-	2	13	2
EEG↓	3	-	6	-	2
CEP↓	6	12	6	25	2
SEP↓	20	12	20	25	10
ECG Δ	-	-	✓	-	-
$\overline{BP}$ ↑	13	-	-	-	-
$\overline{BP}$ ↓	-	-	6	-	-
$\overline{BP}$ Δ on com- pression	-20	-25	-5	-10	-25
Fluid Balance	+270	-20	+210	+25	+290
Pre-℞ Fluid	245	30	130	20	210
℞ Fluid	65	100	140	60	180
Fluid Out	140	150	60	65	100

TABLE A2-5

TREATMENT WITH PO_2 3.0 BAR AT 5.0 BAR

GENERAL DESCRIPTIVE DATA

DOG	180	181	182	183	184
Weight	11.3	10.4	11.3	13.6	12.2
Bottom Time	15	15	15	15	15
Ascent Time	5.0	5.6	5.3	5.2	5.0
2nd Bottom Time	9	-	-	-	-
2nd Ascent Time	6.0	-	-	-	-
RVP↑ Time	5	9	-	2	-
CSFP↑	5	9	1	1	2
EEG↓	1	-	13	3	3
CEP↓	1	11	13	8	3
SEP↓	19	9	13	17	4
ECG Δ	✓	-	-	-	7
$\overline{BP}$ ↑	19	10	-	-	-
$\overline{BP}$ ↓	5	15	-	-	-
$\overline{BP}$ Δ on compression	-50	+35	-15	-15	-15
Fluid Balance	+472	+305	+30	+120	+155
Pre-Ⓑ Fluid	380	120	0	200	130
Ⓑ Fluid	320	285	150	70	145
Fluid out	228	100	120	150	120

TABLE A3-1

TREATMENT WITH PO_2 1.0 BAR AT 5.0 BAR

MONITORED PHYSIOLOGICAL VARIABLES

DOG	140	141	142	143	144
CONTROL					
$\overline{BP}$	122	115	120	142	110
RVP	15/0	37/16	26/0	34/10	8/0
CSFP	7	12	18	4	5
PP	115	103	102	138	105
HR	156	108	96	90	120
f	22	26	4	7	9
$F_{ET}CO_2$	4.2	3.3	3.8	4.4	3.8
ARRIVE SURFACE					
$\overline{BP}$	120	98	125	117	112
RVP	14/0	24/2	22/0	22/2	6/0
CSFP	5	10	16	7	15
PP	115	88	109	110	97
HR	160	110	105	120	120
f	18	7	11	10	9
$F_{ET}CO_2$	4.0	3.8	4.0	4.1	4.3
LOWEST PRE-R					
$\overline{BP}$	90	90	93	77	85
RVP	16/0	20/2	21/0	22/0	6/0
CSFP	5	12	16	7	12
HR	160	110	105	120	120
f	15	13	4	7	8
$F_{ET}CO_2$	3.6	3.8	3.6	2.6	3.2
HIGHEST PRE-R					
$\overline{BP}$	120	220	210	117	113
RVP	48/20	120/20	75/12	38/0	26/12
CSFP	24	24	27	15	36
HR	165	185	132	120	144
f	13	11	8	12	10
$F_{ET}CO_2$	3.8	4.7	4.0	3.7	4.3
PRE-R					
$\overline{BP}$	90	90	93	77	93
RVP	48/20	20/2	31/2	38/0	26/12
CSFP	24	12	27	15	12
PP	66	78	66	62	81
HR	160	185	132	120	144
f	15	11	8	8	9
$F_{ET}CO_2$	3.6	4.4	3.8	3.7	3.4

TABLE A3-1 (Cont.)

DOG	140	141	142	143	144
Bx 15 Min					
$\overline{BP}$	118	93	153	145	127
RVP	26/4	16/4	28/0	22/0	12/8
CSFP	18	6	50	15	44
PP	100	87	103	130	83
HR	156	136	132	96	120
f	18	12	9	10	9
$F_{ET}CO_2$	0.76	0.76	0.94	0.76	0.86
Bx 40 Min					
$\overline{BP}$	118	93	128	137	135
RVP	24/2	16/4	22/0	20/0	10/0
CSFP	13	6	45	15	48
PP	105	87	83	112	87
HR	156	136	120	108	135
f	14	12	9	8	8
$F_{ET}CO_2$	1.08	0.73	1.01	0.98	0.91
Bx 80 Min					
$\overline{BP}$	113	73	118	118	122
RVP	16/0	12/2	19/0	16/0	8/0
CSFP	9	3	40	12	34
PP	104	70	78	106	88
HR	125	120	120	108	140
f	16	11	9	8	9
$F_{ET}CO_2$	1.08	0.51	1.02	0.87	0.91
Bx 120 Min					
$\overline{BP}$	97	65	103	157	130
RVP	16/0	10/2	22/0	25/0	6/0
CSFP	7	2	44	11	30
PP	90	63	59	146	100
HR	125	120	108	156	144
f	10	11	9	9	10
$F_{ET}CO_2$	1.14	0.58	1.00	1.10	0.94

TABLE A3-2

TREATMENT WITH PO_2 1.5 BAR AT 5.0 BAR

MONITORED PHYSIOLOGICAL VARIABLES

DOG	150	151	152	153	154
CONTROL					
$\overline{BP}$	123	123	113	110	125
RVP	20/0	22/2	?	22/0	10/2
CSFP	?	5	8	5	9
PP	(107)	118	105	105	116
HR	108	120	150	150	144
f	11	11	8	10	8
$F_{ET}CO_2$	3.6	3.9	3.4	3.9	3.8
ARRIVE SURFACE					
$\overline{BP}$	135	113	100	123	107
RVP	20/0	22/0	?	24/0	36/2
CSFP	?	1	11	11	17
PP	(127)	112	89	112	90
HR	96	160	120	135	150
f	10	12	5	8	18
$F_{ET}CO_2$	3.2	5.0	3.7	3.5	4.0
LOWEST PRE-B					
$\overline{BP}$	108	67	75	70	80
RVP	20/0	22/0	?	24/0	30/0
CSFP	?	1	10	11	14
HR	132	144	120	120	150
f	9	6	5	8	10
$F_{ET}CO_2$	2.7	3.5	3.7	3.5	3.6
HIGHEST PRE-B					
$\overline{BP}$	167	110	257	190	253
RVP	66/4	32/2	?	105/0	95/10
CSFP	?	7	82	32	60
HR	140	180	156	195	228
f	16	19	9	14	18
$F_{ET}CO_2$	3.3	5.0	4.3	4.9	4.0
PRE-B					
$\overline{BP}$	108	110	149	70	77
RVP	66/4	32/2	?	30/0	32/12
CSFP	?	6	45	27	14
PP	(83)	104	104	43	63
HR	132	150	150	165	168
f	9	6	9	14	12
$F_{ET}CO_2$	3.3	3.5	4.3	4.9	3.8

TABLE A3-2 (cont.)

DOG	150	151	152	153	154
Br 15 Min					
$\overline{BP}$	118	120	98	230	120
RVP	36/0	26/0	?	40/0	34/4
CSFP	?	7	28	30	15
PP	(96)	113	70	200	105
HR	132	144	150	160	180
f	11	12	5	12	10
$F_{ET}CO_2$	0.82	1.02	0.87	1.23	0.82
Br 40 Min					
$\overline{BP}$	117	120	113	143	68
RVP	34/0	26/0	?	25/0	22/0
CSFP	?	4	56	32	11
PP	(97)	116	57	111	57
HR	108	144	96	206	120
f	12	16	8	14	10
$F_{ET}CO_2$	0.82	0.99	0.85	1.07	0.92
Br 80 min					
$\overline{BP}$	105	120	103	108	68
RVP	20/0	22/0	?	24/0	18/0
CSFP	?	5	48	28	11
PP	(85)	115	55	80	57
HR	132	144	108	194	120
f	11	12	7	14	10
$F_{ET}CO_2$	0.83	1.00	0.82	1.08	0.92
Br 120 Min					
$\overline{BP}$	112	125	122	107	72
RVP	22/0	26/0	?	25/0	8/0
CSFP	?	3	45	26	11
PP	(96)	122	77	81	61
HR	144	180	120	160	120
f	14	14	6	14	8
$F_{ET}CO_2$	0.84	1.00	0.87	0.95	0.86

TABLE A3-3

TREATMENT WITH PO_2 2.0 BAR AT 5.0 BAR

MONITORED PHYSIOLOGICAL VARIABLES

DOG	160	161	162	163	164
CONTROL					
$\overline{BP}$	118	127	122	122	102
RVP	24/0	22/2	14/1	20/0	22/2
CSFP	2	2	4	11	4
PP	116	125	118	111	98
HR	120	108	110	140	108
f	8	15	17	9	11
$F_{ET}CO_2$	3.7	4.0	4.1	4.0	4.1
ARRIVE SURFACE					
$\overline{BP}$	108	130	130	140	120
RVP	22/0	24/7	14/0	12/0	20/0
CSFP	5	2	2	9	8
PP	103	128	128	131	112
HR	120	108	160	108	120
f	10	12	18	6	7
$F_{ET}CO_2$	4.1	4.0	3.8	4.2	4.2
LOWEST PRE-R					
$\overline{BP}$	97	113	125	120	87
RVP	22/0	22/5	14/0	22/0	20/0
CSFP	9	2	2	9	6
HR	120	108	140	108	120
f	8	12	15	12	10
$F_{ET}CO_2$	3.2	3.6	3.8	3.2	4.2
HIGHEST PRE-R					
$\overline{BP}$	108	150	133	140	123
RVP	26/0	32/8	24/2	22/0	60/0
CSFP	9	5	8	28	14
HR	120	120	160	144	135
f	12	15	18	9	10
$F_{ET}CO_2$	4.1	4.2	3.8	4.4	4.9
PRE-R					
$\overline{BP}$	105	110	125	133	87
RVP	26/0	25/4	24/2	20/0	48/0
CSFP	8	5	8	28	12
PP	97	105	117	105	75
HR	120	120	140	144	120
f	11	14	10	9	7
$F_{ET}CO_2$	3.2	4.2	3.8	4.4	4.9

TABLE A3-3 (Cont)

DOG	160	161	162	163	164
R 15 min					
$\overline{BP}$	97	92	112	138	143
RVP	20/0	28/6	14/0	18/0	26/0
CSFP	?	3	6	18	9
PP	(90)	89	106	120	134
HR	120	120	140	144	108
f	11	10	15	12	9
$F_{ET}CO_2$	0.69	1.05	0.95	0.97	0.90
R 40 Min					
$\overline{BP}$	112	123	125	123	123
RVP	20/0	20/8	12/0	16/0	22/0
CSFP	?	1	5	16	11
PP	(96)	122	120	107	112
HR	120	96	140	108	105
f	10	12	15	11	9
$F_{ET}CO_2$	0.63	1.05	1.14	0.80	0.94
R 80 Min					
$\overline{BP}$	112	123	115	113	118
RVP	20/0	20/6	10/0	14/0	22/0
CSFP	3	?	1	14	11
PP	109	117	114	99	107
HR	84	96	140	108	108
f	7	12	12	9	8
$F_{ET}CO_2$	0.95	0.84	0.86	0.86	1.00
R 120 Min					
$\overline{BP}$	108	125	120	120	115
RVP	16/0	22/6	10/0	14/0	20/0
CSFP	1	1	1	13	12
PP	107	124	119	107	103
HR	108	96	144	105	120
f	8	13	10	10	8
$F_{ET}CO_2$	0.97	0.84	0.99	0.89	1.18

TABLE A3-4

TREATMENT WITH PO_2 2.5 BAR AT 5.0 BAR

MONITORED PHYSIOLOGICAL VARIABLES

DOG	170	171	172	173	174
CONTROL					
$\overline{BP}$	108	132	107	117	100
RVP	22/0	30/12	35/5	20/0	30/4
CSFP	14	1	10	8	5
PP	84	131	97	109	95
HR	132	144	150	150	120
f	11	16	13	11	8
$F_{ET}CO_2$	3.4	4.2	3.8	3.2	3.5
ARRIVE SURFACE					
$\overline{BP}$	112	113	97	117	100
RVP	18/0	26/14	34/8	18/0	28/4
CSFP	40	2	11	13	12
PP	72	111	86	104	88
HR	132	132	150	132	132
f	12	12	11	9	8
$F_{ET}CO_2$	2.6	4.4	3.3	3.4	3.7
LOWEST PRE-Rx					
$\overline{BP}$	80	108	77	100	70
RVP	18/0	24/12	34/3	18/0	28/4
CSFP	21	2	11	5	12
HR	132	120	144	132	105
f	8	8	4	9	6
$F_{ET}CO_2$	2.9	3.6	2.9	3.4	3.7
HIGHEST PRE-Rx					
$\overline{BP}$	152	118	98	117	100
RVP	60/8	32/22	36/6	28/0	85/30
CSFP	35	7	18	13	38
HR	144	150	160	144	132
f	13	16	12	10	8
$F_{ET}CO_2$	2.9	4.4	3.3	4.4	3.9
PRE-Rx					
$\overline{Bp}$	112	118	92	110	70
RVP	22/0	32/22	37/4	28/0	38/6
CSFP	25	7	11	11	?
PP	87	111	81	99	(57)
HR	140	120	144	144	105
f	11	16	11	10	6
$F_{ET}CO_2$	3.1	4.2	3.3	4.4	3.9

TABLE A3-4 (Cont)

DOG	170	171	172	173	174
B 15 min					
$\overline{BP}$	115	118	97	113	120
RVP	25/0	22/10	36/7	20/0	32/8
CSFP	25	?	30	12	18
PP	90	(100)	67	101	102
HR	150	120	144	132	96
f	15	13	8	10	8
$F_{ET}CO_2$	0.77	0.96	0.86	0.95	0.91
B 40 Min					
$\overline{BP}$	110	118	92	117	143
RVP	20/0	22/10	34/6	20/0	34/7
CSFP	29	?	30	7	12
PP	79	(100)	62	110	131
HR	132	110	144	132	108
f	10	15	9	10	7
$F_{ET}CO_2$	0.80	0.68	0.87	1.07	0.97
B 80 Min					
$\overline{BP}$	97	133	87	107	143
RVP	18/0	22/8	30/6	16/0	36/10
CSFP	28	?	31	14	10
PP	69	(118)	56	93	133
HR	120	132	135	132	120
f	8	16	9	10	7
$F_{ET}CO_2$	0.72	0.67	0.78	1.07	0.96
B 120 Min					
$\overline{BP}$	80	138	93	100	112
RVP	16/0	22/8	36/8	16/0	26/4
CSFP	35	?	31	13	10
PP	45	(120)	62	87	102
HR	120	132	132	115	140
f	7	18	8	10	8
$F_{ET}CO_2$	0.87	0.67	0.85	0.90	1.00

TABLE A3-5

TREATMENT WITH PO_2 3.0 BAR AT 5.0 BAR

MONITORED PHYSIOLGICAL VARIABLES

DOG	180	181	182	183	184
CONTROL					
$\overline{BP}$	107	88	123	125	108
RVP	18/0	30/12	34/0	22/0	28/4
CSFP	5	5	18	3	4
PP	104	83	105	122	104
HR	120	180	135	105	120
f	11	14	10	9	10
$F_{ET}CO_2$	4.3	4.0	3.8	3.9	4.3
ARRIVE SURFACE					
$\overline{BP}$	110	93	147	118	100
RVP	20/0	20/0	20/0	16/0	22/0
CSFP	20	?	17	11	4
PP	90	(81)	130	107	96
HR	110	150	140	120	120
f	11	14	7	8	10
$F_{ET}CO_2$	4.0	4.1	4.1	2.5	3.6
LOWEST PRE-Rx					
$\overline{BP}$	75	70	113	110	88
RVP	18/0	20/0	16/0	16/0	20/0
CSFP	12	?	17	11	4
HR	170	110	140	120	105
f	10	6	7	8	9
$F_{ET}CO_2$	4.2	4.1	4.1	2.5	3.5
HIGHEST PRE-Rx					
$\overline{BP}$	127	130	147	123	100
RVP	60/2	32/4	20/0	34/0	28/0
CSFP	24	?	32	30	11
HR	170	180	156	144	120
f	12	6	9	11	10
$F_{ET}CO_2$	4.2	4.1	5.2	3.4	3.8
PRE-Rx					
$\overline{BP}$	80	70	113	110	87
RVP	34/0	24/0	20/0	34/0	24/0
CSFP	12	?	32	24	6
PP	68	(55)	81	86	81
HR	170	180	156	144	105
f	10	6	8	8	9
$F_{ET}CO_2$	4.0	4.1	5.2	3.4	3.6

TABLE A3-5

DOG	180	181	182	183	184
B 15 Min					
$\overline{BP}$	128	98	148	140	110
RVP	41/0	28/4	32/0	32/2	18/0
CSFP	42	?	18	22	13
PP	86	(78)	130	118	97
HR	180	180	132	84	84
f	12	16	9	7	10
$F_{ET}CO_2$	1.03	1.00	0.83	0.92	0.95
B 40 Min					
$\overline{BP}$	102	103	150	125	120
RVP	20/0	20/0	24/0	28/0	18/0
CSFP	26	?	18	20	18
PP	76	(90)	132	105	102
HR	144	180	144	90	105
f	12	15	9	7	9
$F_{ET}CO_2$	0.84	0.86	0.80	0.95	1.00
B 80 Min					
$\overline{BP}$	90	113	138	137	123
RVP	12/0	22/2	20/0	28/0	20/0
CSFP	22	?	16	20	19
PP	68	(100)	122	117	104
HR	132	110	144	96	105
f	9	16	10	8	10
$F_{ET}CO_2$	0.77	0.84	0.90	0.98	1.01
B 120 Min					
$\overline{BP}$	73	131	135	148	110
RVP	12/0	20/2	28/0	26/2	18/0
CSFP	16	?	12	20	26
PP	57	(117)	123	128	84
HR	120	110	140	132	105
f	8	18	10	9	9
$F_{ET}CO_2$	1.09	0.36	0.82	0.95	1.00

TABLE A4-1

TREATMENT WITH PO_2 1.0 BAR AT 5.0 BAR

ARTERIAL BLOOD ANALYSIS

DOG	140	141	142	143	144
CONTROL					
Hct	50	45	46	46	42
pH	7.41	7.43	7.36	7.33	7.40
$PaCO_2$	31	40	32	35	33
PaO_2	91	93	98	89	101
PRE-Bx					
Hct	55	60	56	47	42
pH	7.42	7.25	7.28	7.21	7.38
$PaCO_2$	30	54	43	52	32
PaO_2	104	68	69	52	108
Bx 40 Min					
Hct	57	52	48	50	49
pH	7.36		7.35		7.35
$PaCO_2$	34		39		33
PaO_2	221		227		210
Bx 80 Min					
Hct	51	50	48	50	51
pH	7.36	7.43	7.35	7.42	7.37
$PaCO_2$	34	48	39	34	34
PaO_2	221	209	227	196	215

TABLE A4-2

TREATMENT WITH PO_2 1.5 BAR AT 5.0 BAR

ARTERIAL BLOOD ANALYSIS

DOG	150	151	152	153	154
CONTROL					
Hct	40	43	45	47	49
pH	7.44	7.41	7.35	7.36	7.41
$PaCO_2$	32	33	32	41	34
PaO_2	93	96	103	84	86
PRE-R					
Hct	55	49	61	56	64
pH	7.29	7.32	7.28	7.34	7.32
$PaCO_2$	36	40	34	42	37
PaO_2	75	75	96	63	92
R 40 Min					
Hct	41	41	48	54	50
pH	7.46	7.32			7.40
$paCO_2$	31	39			36
PaO_2	302	232			249
R 80 Min					
Hct	41	45	44	52	50
pH	7.46	7.35	7.38	7.35	7.40
$PaCO_2$	31	37	32	53	36
PaO_2	302	290	357	261	249

TABLE A4-3

TREATMENT WITH PO_2 2.0 BAR AT 5.0 BAR

ARTERIAL BOOD ANALYSIS

DOG	160	161	162	163	164
CONTROL					
Hct	45	46	42	43	33
pH	7.34	7.36	7.43	7.37	7.40
$PaCO_2$	34	34	40	36	29
PaO_2	92	89	89	95	96
PRE-Bx					
Hct	47	55	48	44	47
pH	7.42	7.35	7.33	7.32	7.30
$PaCO_2$	32	35	50	41	40
PaO_2	104	98	82	87	77
Bx 40 Min					
Hct	48	44	41	47	42
pH	7.45	7.33	7.31	7.43	
$PaCO_2$	26	38	55	28	
PaO_2	392	284	360	378	
Bx 80 Min					
Hct	46	44	41	46	42
pH	7.39	7.39	7.34	7.35	7.35
$PaCO_2$	33	36	50	35	40
PaO_2	375	442	352	372	443

TABLE A4-4

TREATMENT WITH PO_2 2.5 BAR AT 5.0 BAR

ARTERIAL BLOOD ANALYSIS

DOG	170	171	172	173	174
CONTROL					
Hct	44	44	52	45	44
pH	7.46	7.40	7.43	7.42	7.35
$PaCO_2$	28	34	30	32	35
PaO_2	101	93	98	99	85
PRE-B					
Hct	46	45	46	45	48
pH	7.37	7.25	7.41	7.25	7.27
$PaCO_2$	32	47	31	45	41
PaO_2	109	85	109	82	83
B 40 Min					
Hct	38	46	45	45	45
pH	7.41	7.37			7.36
$PaCO_2$	30	42			37
PaO_2	433	387			409
B 80 Min					
Hct	37	45	44	45	54
pH	7.42	7.39	7.40	7.43	7.33
$PaCO_2$	29	40	30	37	34
PaO_2	417	417	405	283	376

TABLE A4-5

TREATMENT WITH PO_2 3.0 BAR AT 5.0 BAR

ARTERIAL BLOOD ANALYSIS

DOG	180	181	182	183	184
CONTROL					
Hct	44	41	43	46	49
pH	7.40	7.37	7.42	7.37	7.41
$PaCO_2$	36	39	30	33	34
PaO_2	93	88	101	92	97
PRE-B					
Hct	47	44	53	52	49
pH	7.31	7.22	7.33	7.36	7.37
$PaCO_2$	42	52	38	34	34
PaO_2	83	72	86	104	100
B 40 Min					
Hct	52	42	50	48	47
pH	7.42			7.35	7.38
$PaCO_2$	30			38	33
PaO_2	521			443	415
B 80 Min					
Hct	49	41	48	50	51
pH	7.48	7.32	7.43	7.35	7.38
$PaCO_2$	27	52	30	36	34
PaO_2	428	404	483	433	436

APPENDIX B

INDIVIDUAL DATA - PRESSURE STUDY

TABLE

B1 - Spinal Evoked Potential - Primary Lesion

B2 - General Descriptive Data

B3 - Monitored Physiological Variables

B4 - Arterial Blood Analysis

- 1 P 3.0 bar

- 2 P 5.0 bar

- 3 P 7.0 bar

- 4 P 2.8 bar

SYMBOLS AND UNITS

As for Appendix A

TABLE B1-1

TREATMENT WITH PO_2 2.0 BAR AT 3.0 BAR

SPINAL EVOKED POTENTIAL - PRIMARY LESION

DOG	200	201	202	203	204
SEP RECORD	RP-L	LP-L	LP-L	RP-L	LP-L
EVOKED POTENTIAL AS PERCENT OF CONTROL					
Pre-Pre-Diagnosis	98.8	100.0	90.2	102.5	104.1
Pre Diagnosis	109.5	115.6	86.4	95.1	105.0
Diagnosis (D)	69.0	95.0	73.7	79.3	60.1
Pre-R	0	0	[34.9]	23.6	10.4
R 15 min	104.5	88.1	78.1	70.9	52.5
R 40 min	94.5	88.1	112.5	91.9	59.3
R 80 min	61.8	82.5	111.8	80.9	64.9
R 120 min	30.6	83.7	97.8	86.2	50.2
LOSS OF SEP AND RECOVERY					
% Loss	100.0	100.0	65.1	76.4	89.6
% Recovered @ 15	100.0	88.1	43.2	47.3	42.1
40	94.5	88.1	65.1	68.3	48.9
80	61.8	82.5	65.1	57.3	54.5
120	30.6	83.7	62.9	62.6	39.8
RATIO OF RECOVERY TO LOSS AS A PERCENT					
15 min	100.0	88.1	66.4	61.9	47.0
40 min	94.5	88.1	100.0	89.4	54.6
80 min	61.8	82.5	100.0	75.0	60.8
120 min	30.6	83.7	96.6	81.9	44.4
ABSOLUTE CHANGE					
Pre-Pre-D to Pre-D	+10.7	+15.6	-3.8	-7.4	+0.9
Pre-D to D	-40.5	-20.6	-12.7	-15.8	-44.9
D to Pre-R	-69.0	-95.0	-2.5	-55.7	-49.7
Loss over Compression	0	0	-36.3	0	0
TIME INTERVALS (Min)					
From Surface to D	8	23	18	17	11
Pre-D to D	4	4	2	4	5
D to R	15.7	16	15.3	15	17
Last SEP to R	4	0	1	1	1

TABLE B1-2

TREATMENT WITH PO_2 2.0 BAR AT 5.0 BAR

SPINAL EVOKED POTENTIAL - PRIMARY LESION

DOG	211	213	126	127	128
SEP RECORD	LP-L	RP-L	LP-L	LP-L	LP-L
EVOKED POTENTIAL AS PERCENT OF CONTROL					
Pre-Pre-Diangnosis	85.4*	99.5*	86.8	93.6	90.5
Pre-Diagnosis	83.5	91.9	83.8	88.2	93.2
Diagnosis (D)	91.1	83.4	71.7	67.1	90.4
Pre-R	1.2	[48.2]	4.8	22.8	71.4
R 15 min	70.6	60.8	87.8	73.4	79.5
R 40 min	61.5	57.7	93.5	75.2	79.0
R 80 min	69.6	54.6	92.8	70.4	85.8
R 120 min	70.6	55.0	40.0	75.8	90.4
LOSS OF SEP AND RECOVERY					
% Loss	98.2	51.8	95.2	77.2	28.6
% Recovered @ 15	69.4	12.6	83.0	50.6	8.1
40	60.3	9.5	88.7	52.4	7.6
80	68.4	6.4	88.0	47.6	14.4
120	69.4	6.8	85.2	53.0	19.0
RATIO OF RECOVERY TO LOSS AS A PERCENT					
15 min	70.7	24.3	87.2	65.5	28.3
40 min	61.4	18.3	93.2	67.9	26.6
80 min	69.7	12.4	92.4	61.7	51.7
120 min	70.7	13.1	99.5	68.7	66.4
ABSOLUTE CHANGE					
Pre-Pre-D to Pre-D	-1.9	-7.6	-3.0	-5.4	+2.7
Pre-D to D	+7.6	-8.5	-12.1	-21.1	-2.8
D to Pre-R	-89.9	-13.8	-66.9	-44.3	-19.0
Loss over compression	0	-21.4	0	0	0
TIME INTERVALS (Min)					
From Surface to D	6	6	29	30	17
Pre-De to D	4	4	5	4	4
D to R	16	15	15.5	17	15
Last SEP to R	1	6	1	2	1

TABLE B1-3

TREATMENT WITH PO_2 2.0 BAR AT 7.0 BAR

SPINAL EVOKED POTENTIAL - PRIMARY LESION

DOG	220	221	222	224	225
SEP RECORD	RP-L	RP-L	LP-L	LP-L	RP-L
EVOKED POTENTIAL AS PERCENT OF CONTROL					
Pre-Pre-Diagnosis	95.2*	75.8	92.3*	101.9*	104.6
Pre-Diagnosis	91.2	78.4	93.3*	98.7*	104.9
Diagnosis (D)	67.5	52.4	82.3	90.8	87.3
Pre-Rx	63.5	0	1.0	9.6	6.5
Rx 15 min	75.9	48.1	4.2	10.7	72.9
Rx 40 min	53.1	41.1	11.9	37.0	76.0
Rx 80 min	58.3	50.0	6.8	29.9	58.5
Rx 120 min	70.4	40.7	7.7	31.8	56.0
LOSS OF SEP AND RECOVERY					
% Loss	36.5	100.0	99.0	90.4	93.5
% Recovery @ 15	12.4	48.1	3.2	1.1	66.4
40	-10.4	41.1	10.9	27.4	69.5
80	-5.2	50.0	5.8	20.3	52.0
120	6.9	40.7	6.7	22.2	49.5
RATIO OF RECOVERY TO LOSS AS A PERCENT					
15 min	34.0	48.1	3.2	1.2	71.0
40 min	0	41.1	11.0	30.3	74.3
80 min	0	50.0	5.9	22.5	55.6
120 min	18.9	40.7	6.8	24.6	52.9
ABSOLUTE CHANGE					
Pre-Pre-D to Pre-D	-4.0	+2.6	+1.0	-3.2	-0.3
Pre-D to D	-23.7	-26.0	-11.0	-7.9	-17.6
D to Pre-Rx	-4.0	-52.4	-81.3	-81.2	-80.8
Loss over compression	0	0	0	0	0
TIME INTERVALS (Min)					
From Surface to D	16	14	2	3	13
Pre-D to D	14	5	2*	3*	5
D to Rx	15	16	16	15	15
Last SEP to Rx	3	0	0	2	4

TABLE B1-4

TREATMENT WITH PO_2 2.8 BAR AT 2.8 BAR

SPINAL EVOKED POTENTIAL - PRIMARY LESION

DOG	231	232	233	234	235
SEP RECORD	LP-L	RP-L	LP-L	LP-L	LP-L
EVOKED POTENTIAL AS PERCENT OF CONTROL					
Pre-Pre-Diagnosis	72.1	91.4*	88.9	110.1*	110.3
Pre-Diagnosis	68.8	80.0	90.3	111.0	101.8
Diagnosis (D)	65.7	117.9	59.0	103.4	86.9
Pre-Bk	0	[10.1]	35.4	[41.1]	7.3
Bk 15 min	41.4	27.2	55.0	44.8	65.0
Bk 40 min	53.1	21.8	69.6	72.9	62.4
Bk 80 min	55.6	25.0	72.3	74.4	68.1
Bk 120 min	55.4	26.2	79.3	47.2	63.1
LOSS OF SEP AND RECOVERY					
% Loss	100.0	89.9	64.6	58.9	92.7
% Recovered @ 15	41.4	17.1	19.6	3.7	57.7
40	53.1	11.7	34.2	31.8	55.1
80	55.6	14.9	36.9	33.3	60.8
120	55.4	16.1	43.9	6.1	55.8
RATIO OF RECOVERY TO LOSS AS A PERCENT					
15 min	41.4	19.0	30.3	6.3	62.2
40 min	53.1	13.0	52.9	54.0	59.4
80 min	55.6	16.6	57.1	56.5	65.6
120 min	55.4	17.9	68.0	10.4	60.2
ABSOLUTE CHANGE					
Pre-Pre-D to Pre-D	-3.3	-11.4	+1.4	+0.9	-8.5
Pre-D to D	-2.1	+37.9	-31.3	-7.6	-14.9
D to Pre-Bk	-65.7	-106.2	-23.6	-51.4	-79.6
Loss over compression	0	-1.6	0	-10.9	0
TIME INTERVALS (Min)					
From Surface to D	27	6	20	6	22
Pre-D to D	5	4	5	5	4
D to Bk	16	17	15	15	16
Las SEP to Bk	1	2	2	2	1

TABLE B2-1

TREATMENT WITH PO_2 2.0 BAR AT 3.0 Bar

GENERAL DESCRIPTIVE DATA

DOG	200	201	202	203	204
Weight (kg)	11.8	10.9	13.6	10.0	10.4
Bottom time (min)	15	15	15	15	15
Ascent time	5.3	5.4	5.7	5.5	5.6
2nd Bottom time	-	-	9	-	-
2nd Ascent time	-	-	5.6	-	-
RVP ↑ Time (min)	6	-	18	-	10
CSFP ↑	-	14	18	17	10
EEG ↓	-	14	9	8	-
CEP ↓	8	27	16	11	11
SEP ↓	8	23	18	17	11
ECG Δ	-	-	-	-	21
$\overline{BP}$ ↑	23	-	20	-	25
$\overline{BP}$ ↓	-	-	-	-	-
$\overline{BP}$ Δ on compression(mm Hg)	-35	-15	-50	-20	-60
Fluid Balance (ml)	+360	+10	-20	+25	+10
Pre-℞ Fluid	80	0	0	125	130
℞ Fluid	330	60	230	200	130
Fluid Out	40	50	250	300	250

TABLE B2-2

TREATMENT WITH PO_2 2.0 BAR AT 5.0 BAR

GENERAL DESCRIPTIVE DATA

DOG	211	213	216	217	218
Weight	10.9	14.5	10.9	10.9	10.9
BottomTime	15	15	15	15	15
Ascent time	5.6	5.5	5.5	5.6	5.5
2nd Bottom time	-	9	-	-	-
2nd Ascent time	-	5.6	-	-	-
RVP↑ Time	5	6	-	-	17
CSFP↑	5	-	-	9	9
EEG↓	7	-	-	-	9
CEP↓	1	6	29	30	9
SEP↓	5	6	29	30	17
ECG Δ	-	-	41	29	17
$\overline{BP}$ ↑	-	-	-	-	-
$\overline{BP}$ ↓	-	-	-	-	-
$\overline{BP}$ Δ on compression	-70	+10	-5	+10	0
Fluid Balance	+75	+138	0	+300	+185
Pre-℞ Fluid	80	38	0	140	30
℞ Fluid	120	200	60	270	280
Fluid Out	125	100	60	110	125

TABLE B2-3

TREATMENT WITH PO_2 2.0 BAR AT 7.0 BAR

GENERAL DESCRIPTIVE DATA

DOG	220	221	222	224	225
Weight	12.7	10.0	12.0	10.5	11.8
Bottom time	15	15	15	15	15
Ascent time	5.0	5.7	5.6	5.5	5.6
2nd Bottom time	8	-	-	-	-
2nd Ascent time	5.2	-	-	-	-
RVP ↑ Time	-	11	17	-	-
CSFP ↑	5	11	-	18	3
EEG ↓	3	-	17	2	3
CEP ↓	3	21	11	2	3
SEP ↓	17	17	2	3	13
ECG Δ	9	-	-	18	3
$\overline{BP}$ ↑	-	-	-	-	-
$\overline{BP}$ ↓	-	-	-	-	-
$\overline{BP}$ Δ on compression	+15	-10	0	-50	0
Fluid Balance	+130	+165	+125	+110	+10
Pre-℞ Fluid	320	40	140	220	70
℞ Fluid	70	160	110	100	40
Fluid Out	260	35	125	210	100

TABLE B2-4

TREATMENT WITH PO_2 2.8 BAR AT 2.8 BAR

GENERAL DESCRIPTIVE DATA

DOG	231	232	233	234	235
Weight	10.4	13.2	12.3	12.7	11.8
Bottom time	15	15	15	15	15
Ascent time	5.7	5.5	5.6	5.6	5.7
2nd Bottom time	-	-	9	-	-
2nd Ascent time	-	-	5.5	-	-
RVP ↑ Time	13	7	4	14	22
CSFP ↑	-	7	-	11	6
EEG ↓	-	-	4	2	-
CEP ↓	38	7	4	6	27
SEP ↓	28	7	20	6	22
ECG Δ	-	-	-	14	38
$\overline{BP}$ ↑	-	-	35	14	-
$\overline{BP}$ ↓	-	-	-	-	-
$\overline{BP}$ Δ on compression	0	-30	-30	-60	-25
Fluid Balance	-60	-45	-100	+165	+60
Pre-℞ Fluid	0	40	70	110	0
℞ Fluid	40	140	30	130	160
Fluid Out	100	225	200	75	100

TABLE B3-1

TREATMENT WITH PO_2 2.0 BAR AT 3.0 BAR

MONITORED PHYSIOLOGICAL VARIABLES

DOG	200	201	202	203	204
CONTROL					
$\overline{BP}$	100	120	152	123	155
RVP	34/0	21/0	45/0	22/0	21/4
CSFP	13	2	2	3	8
PP	87	118	150	120	147
HR	120	156	144	135	150
f	8	10	9	9	13
$F_{ET}CO_2$	3.56	4.18	4.07	3.94	3.60
ARRIVE SURFACE					
$\overline{BP}$	113	115	128	105	130
RVP	96/0	23/0	32/0	20/0	?
CSFP	24	6	3	10	16
PP	89	109	125	95	114
HR	144	144	120	132	135
f	7	8	7	5	8
$F_{ET}CO_2$	2.18	3.74	3.85	3.61	3.85
LOWEST PRE-R					
$\overline{BP}$	113	107	115	88	118
RVP	80/0	22/0	32/0	20/0	?
CSFP	10	3	1	4	9
HR	144	140	108	105	135
f	5	8	6	5	7
$F_{ET}CO_2$	2.18	3.74	3.79	3.23	2.66
HIGHEST PRE-R					
$\overline{BP}$	147	123	170	105	185
RVP	170/0	28/6	52/4	22/0	49/12
CSFP	22	10	4	10	22
HR	180	144	120	132	135
f	11	10	11	6	11
$F_{ET}CO_2$	3.80	3.90	3.92	3.86	4.10
PRE-R					
$\overline{BP}$	147	123	113	90	185
RVP	170/0	28/6	40/0	20/0	49/12
CSFP	11	10	3	4	22
HPP	136	113	110	86	163
HR	150	144	108	120	135
f	10	9	6	5	11
$F_{ET}CO_2$	3.80	3.75	3.79	3.23	4.10

TABLE B3-1 (Cont.)

DOG	200	201	202	203	204
℞ 15 Min					
$\overline{BP}$	158	117	123	113	138
RVP	200/0	25/3	32/0	33/0	?
CSFP	15	10	1	7	17
PP	143	107	122	106	121
HR	150	150	120	120	150
f	9	7	7	5	7
$F_{ET}CO_2$	1.10	1.62	1.31	1.42	1.70
℞ 40 Min					
$\overline{BP}$	137	113	118	110	123
RVP	60/8	20/2	32/0	34/0	21/4
CSFP	18	10	1	8	18
PP	119	103	117	102	105
HR	144	150	120	120	156
f	8	7	7	5	7
$F_{ET}CO_2$	1.12	1.63	1.34	1.64	1.56
℞ 80 Min					
$\overline{BP}$	133	108	138	118	117
RVP	56/10	18/0	38/2	35/0	22/6
CSFP	18	12	1	8	18
PP	115	96	137	110	99
HR	144	144	132	156	150
f	8	11	8	5	8
$F_{ET}CO_2$	1.12	1.62	1.48	1.68	1.56
℞ 120 Min					
$\overline{BP}$	108	103	117	123	118
RVP	28/4	18/0	32/0	36/1	30/14
CSFP	15	13	1	5	15
PP	93	90	116	118	103
HR	135	135	132	132	132
f	8	8	8	6	11
$F_{ET}CO_2$	1.23	1.66	1.48	1.66	1.62

TABLE B3-2

TREATMENT WITH PO_2 2.0 BAR AT 5.0 BAR

MONITORED PHYSIOLOGICAL VARIABLES

DOG	211	213	126	127	218
CONTROL					
$\overline{BP}$	115	115	107	123	162
RVP	10/0	22/2	17/8	21/1	29/0
CSFP	6	3	4	10	4
PP	109	112	103	113	158
HR	144	132	132	135	108
f	8	9	7	7	12
$F_{ET}CO_2$	3.79	4.21	3.70	3.65	4.10
ARRIVE SURFACE					
$\overline{BP}$	123	120	97	113	157
RVP	12/2	22/0	20/2	18/4	20/4
CSFP	20	7	10	18	17
PP	103	113	87	95	140
HR	144	144	144	120	120
f	8	9	8	5	8
$F_{ET}CO_2$	4.17	5.28	2.40	3.13	4.15
LOWEST PRE-Rx					
$\overline{BP}$	82	113	87	98	108
RVP	12/0	22/0	14/0	14/0	18/0
CSFP	14	3	2	4	14
HR	144	144	135	120	120
f	7	9	6	6	5
$F_{ET}CO_2$	4.17	3.80	2.14	3.25	3.31
HIGHEST PRE-Rx					
$\overline{BP}$	117	127	100	117	162
RVP	20/0	34/0	24/2	22/4	24/0
CSFP	22	3	4	7	20
HR	156	156	144	120	132
f	14	13	9	7	13
$F_{ET}CO_2$	5.31	4.06	2.72	4.17	3.54
PRE Rx					
$\overline{BP}$	117	114	92	98	140
RVP	20/0	34/0	24/2	24/4	21/0
CSFP	22	3	4	7	20
PP	95	111	88	91	120
HR	156	144	135	120	132
f	10	13	6	7	10
$F_{ET}CO_2$	4.68	3.80	2.20	4.00	3.31

TABLE B3-2 (Cont.)

DOG	211	213	216	217	218
Br 15 Min					
$\overline{BP}$	157	135	115	133	182
RVP	17.2	24/0	16/0	20/6	23/4
CSFP	24	3	3	4	22
PP	133	132	112	129	160
HR	120	120	120	120	132
f	10	9	6	9	13
$F_{ET}CO_2$	1.12	0.79	0.72	0.76	0.84
Br 40 Min					
$\overline{BP}$	137	125	130	107	157
RVP	14/0	22/0	20/0	18/5	20/4
CSFP	40	3	4	10	18
PP	97	122	126	97	139
HR	144	132	120	135	120
f	10	9	7	9	12
$F_{ET}CO_2$	1.07	0.88	0.77	0.80	0.89
Br 80 Min					
$\overline{BP}$	123	122	133	102	123
RVP	10/0	22/0	17/0	20/6	18/4
CSFP	50	3	4	14	14
PP	73	119	129	88	109
HR	160	144	132	120	108
f	10	8	6	7	13
$F_{ET}CO_2$	0.98	0.89	0.87	0.92	0.92
Br 120 Min					
$\overline{BP}$	118	120	130	102	127
RVP	10/0	22/0	20/0	20/8	22/5
CSFP	52	3	4	19	12
PP	66	117	126	83	115
HR	150	144	132	135	132
f	10	10	7	8	12
$F_{ET}CO_2$	1.06	0.84	0.80	0.85	0.90

TABLE B3-3

TREATMENT WITH PO_2 2.0 BAR AT 7.0 BAR

MONITORED PHYSIOLOGICAL VARIABLES

DOG	220	221	222	224	225
CONTROL					
$\overline{BP}$	137	115	113	105	147
RVP	82/0	45/0	22/0	30/0	21/0
CSFP	7	8	3	1	1
PP	130	107	110	104	146
HR	108	120	120	108	108
f	7	7	10	8	8
$F_{ET}CO_2$	3.80	4.25	3.79	3.20	3.85
ARRIVE SURFACE					
$\overline{BP}$	110	115	112	95	127
RVP	60/0	90/0	24/0	35/6	30/3
CSFP	33	7	6	4	6
PP	77	108	106	91	121
HR	132	120	120	96	96
f	7	5	8	5	6
$F_{ET}CO_2$	3.00	3.61	4.62	3.03	2.50
LOWEST PRE-R					
$\overline{BP}$	80	108	97	80	113
RVP	60/0	70/0	26/0	10/4	24/4
CSFP	20	5	2	1	5
HR	120	120	120	84	108
f	8	5	7	6	6
$F_{ET}CO_2$	4.03	3.79	4.13	3.01	1.83
HIGHEST PRE-R					
$\overline{BP}$	110	115	112	103	127
RVP	75/0	110/0	34/0	22/5	30/0
CSFP	28	8	2	8	13
HR	150	120	140	100	120
f	14	8	9	8	8
$F_{ET}CO_2$	4.03	3.81	4.13	3.01	2.58
PRE-R					
$\overline{BP}$	82	115	97	103	120
RVP	75/6	110/0	34/0	22/5	28/1
CSFP	20	8	2	8	13
PP	162	107	95	95	107
HR	150	120	140	84	120
f	8	8	7	8	8
$F_{ET}CO_2$	4.03	3.81	4.13	3.01	1.83

TABLE B3-3 (Cont.)

DOG	220	221	222	224	225
R 15 Min					
$\overline{BP}$	143	128	128	127	140
RVP	70/5	95/0	26/1	30/8	30/0
CSFP	40	8	6	42	11
PP	103	120	122	85	129
HR	105	120	120	90	96
f	7	7	12	8	5
$F_{ET}CO_2$	0.70	0.67	0.66	0.59	0.56
R 40 Min					
$\overline{BP}$	127	128	123	120	145
RVP	70/0	80/0	28/1	23/6	26/3
CSFP	34	7	3	36	15
PP	93	121	120	84	130
HR	100	120	120	96	108
f	8	7	13	8	6
$F_{ET}CO_2$	0.82	0.61	0.74	0.60	0.58
R 80 Min					
$\overline{BP}$	110	108	117	122	152
RVP	60/0	80/0	22/0	20/5	26/4
CSFP	37	8	4	38	22
PP	73	100	113	84	130
HR	120	140	120	84	108
f	8	7	14	7	9
$F_{ET}CO_2$	0.71	0.65	0.73	0.62	0.51
R 120 Min					
$\overline{BP}$	120	120	105	122	150
RVP	50/0	95/0	22/0	20/6	24/4
CSFP	32	8	5	44	28
PP	88	112	100	78	122
HR	100	132	120	84	108
f	8	7	13	8	9
$F_{ET}CO_2$	0.84	0.47	0.65	0.63	0.56

TABLE B3-4

TREATMENT WITH PO_2 2.8 BAR AT 2.8 BAR

MONITORED PHYSIOLOGICAL VARIABLES

DOG	231	232	233	234	235
CONTROL					
$\overline{BP}$	143	130	133	97	113
RVP	60/8	30/0	29/3	34/0	24/3
CSFP	28	16	8	8	1
PP	115	114	125	89	112
HR	96	144	108	132	132
f	9	9	9	10	9
$F_{ET}CO_2$	4.20	4.30	4.35	4.21	4.84
ARRIVE SURFACE					
$\overline{BP}$	145	123	120	100	112
RVP	52/0	22/0	23/0	22/0	25/2
CSFP	40	14	13	17	13
PP	105	109	107	83	99
HR	108	156	120	135	132
f	9	8	7	9	7
$F_{ET}CO_2$	4.26	2.48	4.39	3.19	3.98
LOWEST PRE-R					
$\overline{BP}$	117	108	112	90	102
RVP	52/0	18/0	18/0	22/0	25/2
CSFP	30	6	9	12	5
HR	108	150	140	120	135
f	7	6	8	7	7
$F_{ET}CO_2$	3.91	2.55	2.83	4.54	3.44
HIGHEST PRE-R					
$\overline{BP}$	140	110	132	203	110
RVP	60/0	34/2	36/0	115/0	30/5
CSFP	34	15	10	56	15
HR	135	160	150	180	168
f	7	10	12	9	8
$F_{ET}CO_2$	4.26	3.34	3.75	4.57	3.90
PRE-R					
$\overline{BP}$	117	108	132	120	110
RVP	52/0	34/2	36/0	115/0	30/5
CSFP	30	12	10	32	15
PP	87	96	122	88	95
HR	108	150	150	180	168
f	7	8	8	9	7
$F_{ET}CO_2$	3.91	2.55	3.75	4.54	3.56

TABLE B3-4 (Cont.)

DOG	231	232	233	234	235
R 15 Min					
$\overline{BP}$	128	117	158	102	100
RVP	48/0	24/0	32/0	32/8	17/0
CSFP	30	6	8	36	5
PP	98	111	150	66	95
HR	108	120	108	120	135
f	7	8	11	10	7
$F_{ET}CO_2$	1.58	1.58	1.54	1.56	1.34
R 40 Min					
$\overline{BP}$	123	103	140	100	100
RVP	50/0	20/0	26/0	20/0	14/0
CSFP	28	10	9	32	7
PP	95	93	131	68	93
HR	120	135	96	108	144
f	7	8	10	10	7
$F_{ET}CO_2$	1.67	1.86	1.62	1.54	1.52
R 80 Min					
$\overline{BP}$	120	112	123	100	130
RVP	44/0	22/0	24/0	24/2	24/4
CSFP	28	10	7	32	11
PP	92	102	116	68	119
HR	120	150	108	96	150
f	7	8	10	10	8
$F_{ET}CO_2$	1.48	1.47	1.53	1.53	1.51
R 120 Min					
$\overline{BP}$	120	112	127	90	128
RVP	40/0	22/0	22/0	16/0	21/0
CSFP	28	10	8	40	5
PP	92	102	119	50	123
HR	136	144	96	120	132
f	7	8	9	10	8
$F_{ET}CO_2$	1.60	1.59	1.49	1.60	1.40

TABLE B4-1

TREATMENT WITH PO_2 2.0 BAR AT 3.0 BAR

ARTERIAL BLOOD ANALYSIS

DOG	200	201	202	203	204
CONTROL					
Hct (%)	42	41	43	50	44
pH	7.38	7.39	7.36	7.43	7.37
$PaCO_2$ (mm Hg)	32	31	33	34	34
PaO_2	96	92	96	100	84
PRE-B					
Hct	52	43	40	53	47
pH	7.29	7.39	7.35	7.36	7.36
$PaCO_2$	33	31	31	25	40
PaO_2	95	102	109	146	87
B 40 Min					
Hct	50	45	44	60	46
pH	7.41	7.33	7.28	7.32	7.36
$PaCO_2$	27	37	37	38	43
PaO_2	457	387	529	439	505
B 120 Min					
Hct	48	45	41	54	44
pH	7.43	7.38	7.34	7.36	7.34
$PaCO_2$	26	34	39	45	40
PaO_2	521	441	523	501	496

TABLE B4-2

TREATMENT WITH PO_2 2.0 BAR AT 5.0 BAR

ARTERIAL BLOOD ANALYSIS

DOG	211	213	216	217	218
CONTROL					
Hct	49	45	40	44	44
pH	7.37	7.35	7.37	7.40	7.34
$PaCO_2$	32	32	35	33	36
PaO_2	92	100	94	94	101
PRE-R					
Hct	49	45	40	50	51
pH	7.38	7.29	7.41	7.32	7.31
$PaCO_2$	40	43	31	38	38
PaO_2	112	81	101	90	111
R 40 Min					
Hct	56	45	43	45	46
pH	7.35	7.40	7.40	7.48	7.42
$PaCO_2$	38	38	30	26	37
PaO_2	316	375	295	403	376
R 120 Min					
Hct	51	45	43	42	44
pH	7.39	7.34	7.42	7.44	7.43
$PaCO_2$	33	45	30	31	34
PaO_2	321	330	297	607	361

TABLE B4-3

TREATMENT WITH PO_2 2.0 BAR AT 7.0 BAR

ARTERIAL BLOOD ANALYSIS

DOG	220	221	222	224	225
CONTROL					
Hct	43	45	42	41	42
pH	7.35	7.42	7.40	7.35	7.43
$PaCO_2$	30	32	31	40	32
PaO_2	100	90	96	88	85
PRE-R					
Hct	44	46	47	38	42
pH	7.32	7.42	7.30	7.28	7.37
$PaCO_2$	39	31	42	45	35
PaO_2	99	92	78	80	97
R 40 Min					
Hct	40	46	44	43	44
pH	7.21	7.43	7.35	7.50	7.40
$PaCO_2$	60	32	43	32	35
PaO_2	284	256	257	318	309
R 120 Min					
Hct	40	48	43	44	46
pH	7.23	7.38	7.37	7.46	7.41
$PaCO_2$	57	34	45	33	34
PaO_2	248	259	262	295	294

TABLE B4-4

TREATMENT WITH PO_2 2.8 BAR AT 2.8 BAR

ARTERIAL BLOOD ANALYSIS

DOG	231	232	233	234	235
CONTROL					
Hct	48	49	45	42	42
pH	7.40	7.36	7.36	7.37	7.43
$PaCO_2$	35	35	36	35	34
PaO_2	90	90	86	86	100
PRE-R					
Hct	49	50	47	46	45
pH	7.36	7.28	7.22	7.33	7.37
$PaCO_2$	35	41	52	47	40
PaO_2	97	69	49	61	95
R 40 Min					
Hct	47	50	41	45	40
pH	7.35	7.34	7.41	7.38	7.42
$PaCO_2$	40	40	43	37	32
PaO_2	654	316	613	692	226
R 120 Min					
Hct	46	49	47	45	38
pH	7.36	7.33	7.42	7.38	7.38
$PaCO_2$	37	36	36	35	38
PaO_2	631	330	698	674	558

APPENDIX C

PUBLISHED PAPERS

1. The effect of various gases on cortical and spinal somatosensory evoked potentials at pressures up to 10 bar.

2. Remote monitoring of neuraxial function in anesthetized dogs in compression chambers.

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AVIATION, SPACE, and ENVIRONMENTAL MEDICINE

The Effects of Various Gases on Cortical and Spinal Somatosensory Evoked Potentials at Pressures up to 10 bar

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LEITCH, D. R., J. M. HALLENBECK, and L. J. GREENBAUM, JR. *The effects of various gases on cortical and spinal somatosensory evoked potentials at pressures up to 10 bar.* Aviat. Space Environ. Med. 54(2): 105–111, 1983.

The development of dog electrophysiological models for studying the treatment of cerebral arterial air embolism and spinal cord decompression sickness, required that the effects of the treatment gases on spinal and cortical somatosensory evoked potentials (SEP and CEP) be known. We found an inverse linear relationship between CEP amplitude and air pressure to 230 ft. An asymptote was approached when pressure was increased to 300 ft. This effect was not seen with 20% oxy-helium. The waves representing local cord events were depressed to a lesser extent than were the CEPs. We were able to detect an equilibration time in the EP suppression comparable to estimated inert gas wash-in time for the brain. A small depression of CEPs that did not reach significance was seen with exposure to 2.8 bar of oxygen and continuous exposure for up to 120 min caused no further diminution in amplitude than would be caused by time alone.

VISUAL AND AUDITORY evoked responses (VER, AER) have been widely used as measures of inert gas narcosis (6). Somatosensory cortical evoked potentials have been applied in this condition less commonly (14,15). Whether or not evoked potentials provide a true measure of narcosis continues to be debated because they do not necessarily correlate well with independent measures of cortical performance (6). The effect of narcosis is thought to be one of interference with synaptic transmission, primarily in the brain (2,4). It is interesting, however, that although in any given group the overall effect on evoked responses is one of depression, the range of effect can often be very wide, even showing a slight increase above baseline values at pressures of up to 11 bar in some individuals (2). The narcotic effect has also been attributed to oxygen as well as to nitrogen (5,10).

A series of experiments were undertaken to study the relative efficacy of different pressures and gas mixtures in the treatment of cerebral arterial gas embolism (AGE) and spinal cord decompression sickness (DCS). The model used dogs anesthetized with pentobarbital and prepared for the measurement of spinal cord somatosensory evoked potentials (SEP) and cortical somatosensory evoked potentials (CEP) from the peroneal and median nerves. A requirement of the experimental design was that many of the measurements were to be made at pressure so the full range of possible effects of the expected hyperbaric conditions upon the parameters to be measured had to be defined. Most of the observations reported were made during the preparatory phases of DCS experiments but a small number were made during specifically dedicated experiments.

The questions asked were:

a) How much of a depressing effect did various pressures of air have upon CEP and SEP, and what corrections if any should be applied to measurements made at pressure?

b) Is there an equilibration time for the expected changes in EPs following a step change in pressure?

c) Does hyperbaric oxygen have any effect upon EPs?

d) Does prolonged exposure to high pressure air or oxygen have any progressive effect?

e) For comparative purposes, how does 20% oxygen-helium mix affect EPs over the same pressure range as air?

f) Are SEPs and CEPs equally affected, or are any components more affected than others?

MATERIALS AND METHODS

In these studies 61 conditioned male mongrel dogs

weighing between 9 and 21 kg were used. Studies were terminated with the intracardiac injection of saturated KCl solution. The dogs were sedated with xylazine (1.1 $mg \cdot kg^{-1}$, s.c.) and atropine (0.05 $mg \cdot kg^{-1}$, s.c.). They were then anesthetized with sodium pentobarbital (13.5 $mg \cdot kg^{-1}$, i.v.) and maintained on a routine of half the initial dose after 20 min and a maintenance dose of 4 $mg \cdot kg^{-1} \cdot h^{-1}$ given in divided doses at 20-min intervals. Small adjustments to the maintenance regimen were made if required. After intubation, ventilation was maintained with a modified Bird® Mark 7 respirator. The animals were prepared for physiological observations with bilateral femoral arterial cannulation for pressure monitoring and arterial blood sampling. A Millar (7F gauge) pressure tip catheter was introduced via the right femoral vein into the right ventricle. A polyethylene catheter was placed in the left foreleg cephalic vein for the administration of anesthesia and fluids. Rectal temperature was maintained between 37.5 and 39.0°C by means of a hot water circulating plate incorporated into the base of the head-holding stand. The dog was placed prone into the head-holding stand and secured by ear bars. Skin, muscle, and periosteum were cleared from the skull over the right sensorimotor cortex and a stainless steel electrode inserted into a hole drilled into the cancellous bone over either the cortical sensorimotor forelimb area or between the fore and hind limb areas as required. The indifferent electrode was placed into the distal end of the nasal bones. Pairs of sharpened 1-mm diameter stainless steel wires insulated except for 2-3 mm at the tip were hammered into the spinal lamina in the mid-line. These were placed in adjacent intervertebral spaces in the vicinity of L_1, T_8, and C_7. The peroneal and median nerves were stimulated through pairs of 20 gauge stainless steel needles placed percutaneously adjacent to the respective nerves on the left side at the neck of the fibula and the distal end of the humerus. The details of materials and method are reported elsewhere (Leitch, in preparation). Cortical and spinal electrode impedences were less than 2 and 6 kohms, respectively.

A Grass S88 stimulator and two Nicolet Computers of Average Transients (CAT) (Models 1074 and 1072) were driven by a Nicolet Stimulus Pulse Generator (NIC-502). The stimulus at 100 to 120 V (three times motor threshold) and 10 mA was delivered through a Grass Photoelectric Stimulus Isolation and Constant Current Unit (PISU 6C) and directed through a 4-way switching box on the outside of the chamber. The output from all four recording sites was averaged simultaneously on the two CAT's, the three SEPs by the 1074 with a 26-30 ms span and the CEP by the 1072 with a 110 ms span (n = 128). The outputs were observed on two Tektronics oscilloscopes (5110) and recorded on three Hewlett-Packard X-Y plotters (HP 7045 A&B). The signals were amplified to 10^4 by differential amplifiers (NIC-200A) outside the chamber before being further amplified (gain 40) and filtered on a 30-3000 Hz bandpass (NIC-501A). The EP's were recorded with the positive up convention and with a 2-ms delay before stimulation. The primary measurements were peak-to-peak amplitudes of P_1N_1 and N_1P_2 in the CEPs, and of P_1N_1 in the SEPs.

When the animal was placed in the compression chamber, and was stable within the desired range of physiological measurements, between four and six sets of control evoked potentials were obtained for each stimulus site. The chamber was then closed and, with the appropriate breathing gas on line to the ventilator compression with air at a rate of 75 ft/min^{-1} was begun. Modifications to the ventilator allowed control of cycle rate and inspiratory flow rate from outside the chamber so that $F_{ET}CO_2$ was maintained at 3.5-4.5% surface equivalent as measured by a Beckman LB2 CO_2 analyzer. The animals were subjected to the dive profiles shown in Table I.

About 2 min after each pressure change, EP recording was begun. All records were made in pairs. Results are expressed as a percent of mean control EP amplitude values for each dog. One way analysis of variance was performed where a significant difference between groups was sought.

RESULTS

Examples of actual recordings taken from one dog are shown in Fig. 1, where the effect of breathing air at 300 ft may be seen. All animals were maintained within the normal range for rectal temperature, acid-base state, and blood gases.

The records from the six dogs followed at the surface for 5 h, showed a slight tendency for amplitude to fall and variance to increase with time (Table II).

The results from each profile were first studied separately. This revealed that regardless of profile, the effect of any given condition with the same breathing gas, was the same. Therefore, the results from all profiles using the same gas were pooled. At no time was any effect on

TABLE I. DIVE DESCRIPTIONS.

PROFILE	N	DIVE PROFILE [fsw (GAS) x MIN]
1	11	60(O_2)x10; 165(A)x10; 230(A)x45
2	7	230(A)x45
3	17	300(A)x15
4	3	60(O_2)x10; 165(A)x10; 60(O_2)x10; 0(A)x40; 165(A)x10; 60(O_2)x120
5	3	60(A)x10; 60(O_2)x120; 165(A)x10; 0(A)x40; 60(A)x10; 60(O_2)x10; 165(A)x10; 60(O_2)x10
6	3	60(A)x10; 165(A)x120; 60(A)x10
7	9	60(O_2)x20; 165(A)x20; 60(O_2)x20
8	8	165(A)x20; 60(O_2)x20
9	3	230(He)x10; 300(He)x10; 165(He)x10; 60(He)x10; 60(O_2)x10
10	2	60(He)x10; 165(He)x10; 230(He)x10; 300(He)x10
11	6	0(A)x300

All profiles preceeded by 60-100 min control period. Profile 10 followed profile 5, and profile 6 followed profile 9 in the same dogs with a 60 min surface interval. Times are approximate. Breathing gases were (O_2)—100%; (A)—air; (He)—20% O_2/80% He. Total N = 61. In profiles 7 and 8 only Median CEP was recorded.

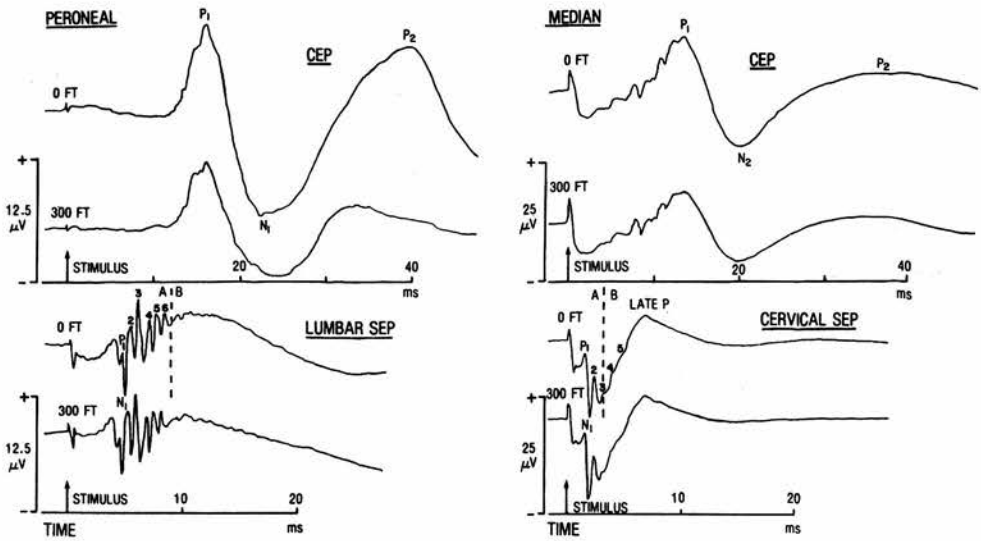

Fig. 1. Records of cortical and spinal evoked potentials resulting from peroneal and median nerve stimulation at 100 v 10 mA at 2.5 Hz (n = 128) in the same dog. Peaks of interest are designated P and N with an arbitrary division to A and B in the SEPs for summing peak to peak amplitude. The first record of each pair was the control record and the second was at 300 ft.

TABLE II. EFFECT OF TIME ON EVOKED POTENTIALS.

			Time Period (hr) 0-1	1-2	2-3	3-4	4-5	Overall	Range of Amplitude μv (MIN) (MAX)
Peroneal CEP	P_1N_1	$\bar{x}$	100.0	93.2	91.9	92.7	90.1	93.6	7
		SE	5.9	5.2	5.7	6.3	8.7	6.9	108
Peroneal CEP	N_1P_2	$\bar{x}$	100.0	97.6	91.9	88.3	92.8	94.5	7
		SE	5.4	5.8	9.6	6.5	7.9	7.4	97
Lumbar SEP	P_1N_1	$\bar{x}$	100.0	97.8	95.9	91.9	90.2	95.2	5
		SE	2.1	3.7	5.4	5.0	5.6	5.0	101
Median CEP	P_1N_1	$\bar{x}$	100.0	101.6	99.6	97.0	97.4	99.1	4
		SE	2.7	5.3	6.3	6.9	8.6	6.0	74
Median CEP	N_1P_2	$\bar{x}$	100.0	98.5	100.2	96.6	96.0	98.3	1
		SE	4.1	5.7	6.0	7.7	7.2	6.3	38
Cervical SEP	P_1N_1	$\bar{x}$	100.0	97.0	94.2	92.5	94.6	95.7	3
		SE	1.4	2.7	2.6	3.0	3.1	2.9	53
Cervical SEP	Late P	$\bar{x}$	100.0	95.8	95.2	94.5	91.9	95.5	3
		SE	2.2	3.9	4.3	5.8	5.4	4.5	113

Expressed as a percent of control. N = 6 2-6 Measurements per dog per period.

latency seen which could be attributed to gas, pressure, or time. The data used in the air and oxygen study were drawn from the first 20 min of any given exposure.

While breathing oxygen at 60 ft (2.8 bar), there was a marginal but insignificant depression of P_1N_1 in peroneal and median CEP, which tended to be restored on returning to air breathing at the surface.

The effects of the various pressures on CEP and SEP in air breathing dogs are shown in Table III and Fig. 2 and 3. There was a significant depression of both P_1N_1 and N_1P_2 proportional to pressure up to 230 ft. It appeared that by 300 ft there was at least a leveling off of the effect if not an actual reversal. When breathing 20% oxyhelium instead of air no effect of pressure was seen (Table IV). In those profiles (4, 5, 7, and 8 in Table I) where dogs were returned to the surface free from the risk of decompression sickness, CEPs returned towards control values upon surfacing.

No significant depression of P_1N_1 was seen in the SEPs. The SEPs measured in air and oxyhelium were almost the same. (Table III and IV and Fig. 3). However, the amplitude of the cervical SEP late P wave was significantly reduced while breathing air, although to a lesser extent than were the CEP's (Table III, and Fig. 3).

The effects of continuous exposure to pressure for up to 2 h are shown in Table V. Neither with continuous oxygen at 60 ft nor air at 165 ft, was there any evidence of an accelerated deterioration beyond that due to time alone as seen at atmospheric pressure. The actual changes seen were comparable with acute changes shown in the pooled data presented in Table III. On return from 2 h of oxygen breathing at 60 ft, to air breathing at atmospheric pressure, there was no change in CEP amplitude so that the final level was comparable with what time alone might produce (Table II).

An attempt was made to detect an effect of inert gas wash-in from the data given in Table VI. Routinely after every step change in pressure, two peroneal CEPs were recorded followed by two median CEPs. If the exposure was longer than 15 min, the cycle was repeated. Table VI contains the results from all three gases at all pressures tested. Firstly, the direction of change between the first and second recordings (peroneal) and third and fourth recordings (median) was tested by chi-square. There were significantly more reductions from first to second recordings than from third to fourth recordings ($P < 0.01$).

TABLE III. EFFECT OF PRESSURE ON EVOKED POTENTIALS WHILE BREATHING AIR OR OXYGEN.

	Depth(fsw)		Surface	60(O_2)	60(A)	165	230	300
Peroneal CEP	P_1N_1	$\bar{x}$	100.0	94.6	95.8	85.6	77.6	85.4
		SE	1.2	2.9	1.4	2.1	3.7	3.2
		n	46	17	5	23	18	17
Peroneal CEP	N_1P_2	$\bar{x}$	100.0	98.2	97.3	86.4	78.3	87.1
		SE	2.1	2.7	2.4	2.4	3.9	2.8
		n	46	17	5	23	18	17
Lumbar SEP	P_1N_1	$\bar{x}$	100.0	99.1	97.6	94.3	91.7	92.6
		SE	1.1	3.2	3.3	2.3	2.7	2.4
		n	45	17	5	23	17	17
Median CEP	P_1N_1	$\bar{x}$	100.0	95.0	99.5	80.8	70.5	68.8
		SE	1.2	2.3	3.4	2.4	2.8	3.3
		n	39	17	5	23	16	12
Median CEP	N_1P_2	$\bar{x}$	100.0	96.9	94.7	82.9	77.8	77.2
		SE	2.3	2.8	4.9	3.3	3.9	6.9
		n	39	17	5	23	16	12
Cervical SEP	P_1N_1	$\bar{x}$	100.0	96.8	100.0	95.6	97.8	97.0
		SE	0.7	1.9	0.6	3.0	3.6	2.3
		n	40	17	5	23	17	12
Cervical Late P SEP		$\bar{x}$	100.0	97.4	103.2	92.4	88.3	90.0
		SE	1.2	1.7	4.4	1.6	1.7	3.6
		n	40	17	5	23	17	12

Percent of mean surface control ± S.E.M. The pooled results from dive profiles 1-6 but excluding the last 80 min of the 120 min studies at 60 ft(O_2) and 165 ft(A). Control data has ≮ 5 replicates per dog and all other entries ≮ 2 replicates.

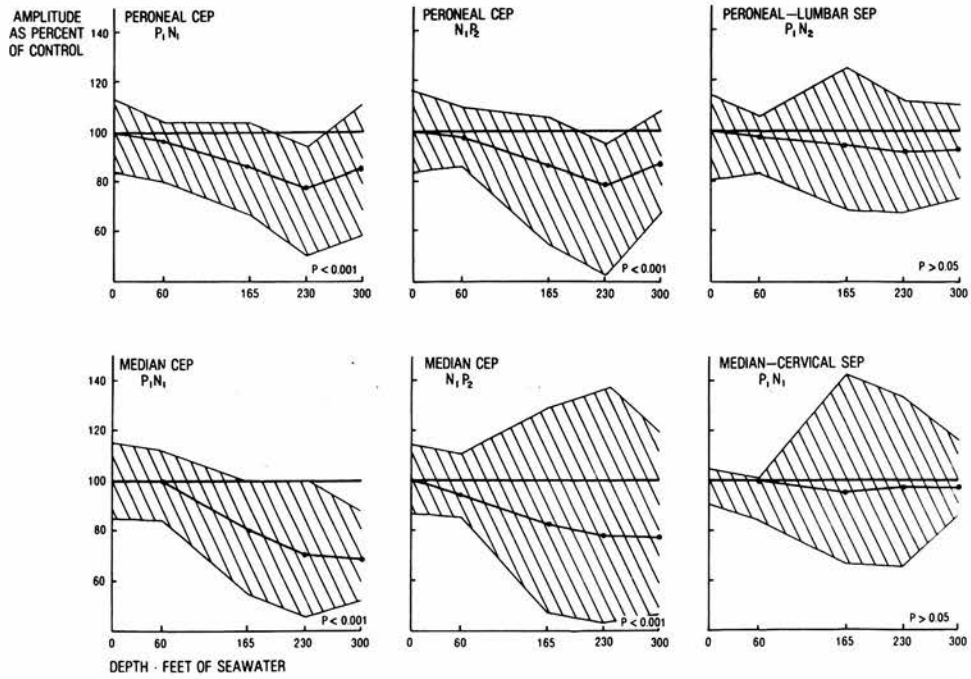

Fig. 2. The mean CEP, P_1N_1 and N_1P_2, and SEP P_1N_1 are shown for peroneal and median nerve stimulation while breathing air at the pressures shown. Results are expressed as percent of mean control values and the shaded area indicates the range of measurements seen. Details of SE and n for each point are given in Table III. The level of significance of the difference between groups by ANOVAR is given on each graph.

This effect was apparent over approximately the first 6 min after a step change of pressure while breathing air. It was not apparent when breathing oxygen or oxy-helium.

There appeared to be a further reduction between the second and third recordings although its significance was not tested because this would have entailed crossing between peroneal and median recordings. This suggests an asymptote for narcotic effect at about 10 min.

In the 230 ft air breathing group, which followed the trend already outlined, it is noteworthy that the next pair of peroneal recordings (No. 5 and 6) were the same (70.8%) as the preceeding median recordings (70.5%) and also the final pair of medians (No. 7 and 8) (69.6%), indicating a plateau.

In a group in which only median CEPs were measured the same observations were made. There was no consistent change seen with oxygen at 60 ft. Mean values for four consecutive measurements (n = 17) were 96.8 ± 4.1, 96.2 ± 4.6, 89.9 ± 4.6, and 94.7 ± 5.6. With air breathing at 165 ft there was again a significant difference for the direction of change by chi-square ($p < 0.001$) between the first and second pairs of recordings. This was also evident by paired "t" test

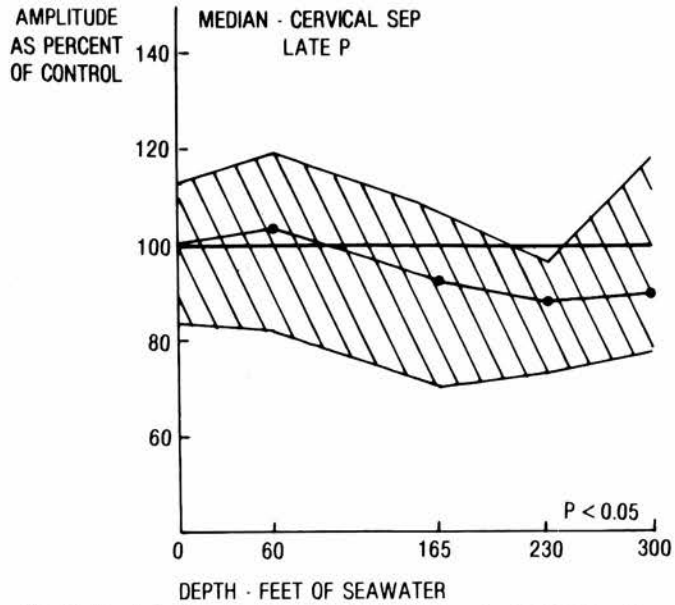

Fig. 3. The late P wave means from the cervical SEP following median nerve stimulation while breathing air at the pressures indicated are shown. Results are expressed as percent of mean control values and the shaded area indicates the range of measurements seen.

($p < 0.01$). The mean values for the four consecutive measurements ($n = 17$) were 86.5 ± 3.4, 79.5 ± 3.4, 77.3 ± 4.6, and 78.1 ± 4.5. Evidence for wash-out was sought in the dogs which went from 165 ft on air to 60 ft on oxygen (profiles 4, 5, 7, and 8 in Table 1). There was an insignificant increase in the group means between first and second recordings of from 1 to 3% following arrival at 60 ft.

In assessing SEP, we began our study using the first of the travelling waves P_1N_1. Later we adopted to a summation of amplitude. We compared P_1N_1 and the summed amplitude (Σ amp) in section A (Fig. 1) in 48 sets of SEP measurements from the 16 dogs entered into the new system. A linear correlation was performed on the data plotting Σ amp against P_1N_1. This produced the relationship $\Sigma \text{ amp} = 22.12 + 0.733(P_1N_1)$ with $r^2 = 0.6686$. At about 79% the Σ amp and P_1N_1 regression lines crossed. The two parameters were not significantly different by paired "t" test ($t = 2.00$ with 47 df).

DISCUSSION

The objective in making these observations, was to explore the effects of breathing nitrogen mixtures and oxygen, on SEP and CEP recordings made during animal experiments studying the treatment of arterial air embolism and decompression sickness. We observed that as deep as 230 ft (8 bar) there was a linear relationship between pressure and the reduction in CEP amplitude

TABLE IV. EFFECT OF PRESSURE ON EVOKED POTENTIALS WHILE BREATHING 20% OXYGEN IN HELIUM.

	Depth(fsw)		Surface	60	165	230	300
Peroneal CEP	P_1N_1	$\bar{x}$	100.0	104.6	101.8	98.5	96.7
		SE	3.0	6.1	5.1	5.0	3.8
Peroneal CEP	N_1P_2	$\bar{x}$	100.0	104.0	102.7	101.3	97.5
		SE	3.0	3.4	5.3	5.9	3.9
Lumbar SEP	P_1N_1	$\bar{x}$	100.0	95.7	94.6	96.0	95.0
		SE	1.4	1.3	2.6	1.5	1.6
Median CEP	P_1N_1	$\bar{x}$	100.0	96.3	95.7	93.4	98.0
		SE	2.1	3.5	4.3	3.5	5.0
Median CEP	N_1P_2	$\bar{x}$	100.0	98.5	98.7	98.6	99.1
		SE	2.9	4.1	7.2	4.3	4.8
Cervical SEP	P_1N_1	$\bar{x}$	100.0	97.2	96.3	98.1	96.0
		SE	0.3	2.2	2.3	1.8	1.9
Cervical Late P SEP		$\bar{x}$	100.0	97.2	96.3	98.1	96.0
		SE	0.3	2.2	2.3	1.8	1.8

Percent of mean surface control ± S.E.M., N = 5. Control data has four replicates per dog and other entries, two replicates.

TABLE V. THE EFFECT OF 2 h EXPOSURE TO 2.8 bar OF OXYGEN AND 6 bar OF AIR ON EVOKED POTENTIALS.

Time Period (Min)			60 fsw - oxygen (N=6) 0-40	41-80	81-120	165 fsw - air (N=3) 0-40	41-80	81-120
Peroneal CEP	P_1N_1	$\bar{x}$	100.6	105.1	106.5	86.7	85.8	83.7
		SD	9.6	18.3	21.0	2.1	2.1	3.6
Lumbar SEP	P_1N_1	$\bar{x}$	93.5	91.9	94.3	92.8	94.7	91.4
		SD	23.4	29.9	28.0	7.8	7.0	5.0
Median CEP	P_1N_1	$\bar{x}$	96.7	92.5	95.7	89.2	88.0	86.6
		SD	12.9	13.7	21.4	4.0	4.5	3.2
Cervical SEP	P_1N_1	$\bar{x}$	96.8	98.9	101.5	94.7	91.6	88.9
		SD	3.6	5.9	6.3	2.9	5.3	7.1
Cervical Late P SEP		$\bar{x}$	98.3	96.7	95.5	93.3	94.6	94.8
		SD	8.0	7.8	6.6	4.0	6.4	6.6

Results expressed as a percent of surface control values ± S.D.

when breathing air. Between 230 ft and 300 ft there appeared to be a leveling off of the amplitude reduction. No significant effect was seen with oxygen at 60 ft or with 20% oxy-helium up to 300 ft. Exposure to oxygen at 60 ft and air at 165 ft for up to 2 hr did not cause any exaggerated loss of amplitude with time. None of the conditions tested caused a significant loss of SEP amplitude either as assessed by P_1N_1 or summed amplitude although there was a downward trend related to pressure. However, the late P wave, representing local cord events (8), was significantly affected by increasing air pressure. We were also able to detect an effect, possibly attributable to inert gas wash-in, in that CEP amplitude decreased over the first 6-10 min after a step pressure increase before plateauing. A hint of the reverse effect was also seen. No effect was seen on peak latency under any condition.

Two facts emerge from the literature regarding evoked potential measurement at pressure. One is that experimental numbers are commonly very small and the other is that reported results are widely divergent even within the same experimental group. Only one group has reported the use of somatosensory cortical evoked potentials in studies of the effects of nitrogen. They reported the effects to be similar to those on other EPs (14,15). All other groups have relied on auditory or visual evoked potentials. Another variable involves the subjects, which have included man, awake animals and anesthetized animals.

Breathing gases from a mask in contrast to ventilation through an endotracheal tube, is also a potential source of variability. The surrounding gas can leak through poor seals; a problem well recognized in older mask designs. Masks are also prone to cause some CO_2 build-up because of the increased dead space, a factor known to exacerbate narcosis (4). Clearly, breathing chamber atmosphere or gas supplied through a cuffed endotracheal tube are the only reliable ways of supplying a precisely known breathing gas. Any circumstances where an animal breathes one gas while surrounded by another will result in some cutaneous transfer, although the effect will undoubtedly be trivial.

In both the median and peroneal CEP results, an approach to an asymptote is suggested between 230 and 300 ft while air breathing. Bennett *et al.* (5) saw a similar effect but regarded it as experimental variation. Kinney *et al.* (13) refer to an asymptote for nitrogen in the region of 300 to 400 ft. There are no clear reasons why this should occur. The possibility of a saturation of the effect of nitrogen seems unlikely at this pressure as behavioural changes continue to increase at greater pressures. If it were not that oxygen is also alleged to be narcotic and should therefore have a synergistic effect (5,10), the possibility of a stimulating effect from the oxygen with a partial pressure approaching 2 bar might be considered as having some reversal effect on the EP suppression by nitrogen. However, the short time scale excludes a mechanism associated with classical acute cerebral oxygen toxicity.

The range of individual responses seen in our data was similar to that reported by Bartus *et al.* (2), where even at a pressure of about 11 bar some records were greater than controls. The degree of mean suppression of groups is also widely variable. Air breathing at 200 to 300 ft has produced EP suppressions ranging from levels similar to ours (1) to twice as great as ours (5,17). We can confirm that the effect of air at pressure on somatosensory CEP is similar to that on auditory and visual CEP. The only report of a latency shift by Kinney *et al.* (12) is at odds with our findings and those of others (1,5,10).

The reported work on EPs while breathing oxy-helium in the pressure range of interest to us has largely been done with awake men and animals (5,17). They report a depression of about 30% in AER at 300 ft and about 20% at 200 ft where we saw no apparent change. It may be that the anesthesia in our animals has already caused that amount of suppression. Certainly if one deducts 30% from those results and also the air results reported by the same authors then our findings are the same. This might suggest a synergistic effect of narcosis with pentobarbital. It may also be that the many extraneous effects of compression, of which the conscious man/animal is aware, could also have an adverse influence upon EP measurement.

Bennett (3) reported a reduction in cat spinal reflex activity during air breathing at pressures of 7-9 bar. He likened the effect to the asphyxia effects on the segmental SEPs recorded from the cord dorsum described by Gelfan and Tarlov (8). Looking at the initial travelling wave

TABLE VI. EFFECT OF INERT GAS WASH-IN ON CORTICAL EVOKED POTENTIAL AMPLITUDE.

Gas		Air				O_2/He				O_2
Depth	(fsw)	60	165	230	300	60	165	230	300	60
Peroneal	1	96.0	87.1	80.1	88.3	101.3	97.1	92.0	92.6	94.0
		1.9	2.3	5.1	4.0	4.8	4.6	3.5	2.7	2.2
	2	95.5	84.2	74.0	85.1	96.6	96.3	94.7	91.1	94.7
		2.2	2.2	3.0	4.9	6.8	5.2	3.9	4.3	2.3
	Δ	−0.5	−2.3	−5.9	−3.2	−4.7	−0.8	+2.7	−1.5	+0.7
Median	3	96.3	82.1	70.6	67.7	96.3	97.3	92.0	88.1	97.2
		3.3	2.5	3.1	3.5	4.3	4.2	5.0	3.9	2.2
	4	96.7	81.2	70.1	69.9	96.8	94.4	91.0	90.1	95.8
		3.1	2.6	3.2	3.3	4.0	5.0	4.8	5.3	2.6
	Δ	+0.4	−0.9	−0.5	+2.2	+0.5	−2.9	−1.0	+2.0	−1.4

Results expressed as percent of mean control value ± S.E.M. The first pair of CEPs (Peroneal) were recorded between 1 and 6 min after arrival at the stated pressure. The second pair of CEPs (Median) were recorded between 6 and 12 min after arrival at the stated pressure. The mean values at 230 ft (Air) for a second pair of peroneal CEPs taken at 20 - 30 min were 70.7 ± 3.29 and 71.0 ± 3.50.

as opposed to the static wave of the root entry in the SEPs and also the summed amplitude of the principal early waves, we saw a slight downward trend in amplitude which was no significant. However, the late slow P wave in the median—cervical SEP showed a significant change inversely related to air pressure. The depression was considerably less than that seen in the CEP at the same pressures. This wave may be related to interneuronal activity and possibly to local reflexes (8). Our findings would therefore tend to corroborate those of Bennett (3). The relationship between the three types of EPs; SEP long tract travelling waves (mostly non-synaptic), SEP late P waves (interneuronal local events), and CEP (multiple synaptic transmission) and the relative effects of narcosis, lend support to the idea that the inert gas effect is the result of interference with synaptic transmission (4). The effect is evidently mostly in the brain, as suggested by Bartus and Kinney (2), where the density of synapses is greater.

The literature appears to contain no references to the ability to detect the effect of inert gas wash-in upon the EPs. The appearance of a plateau by about 8 to 10 min is compatable with opinions regarding the time for inert gas exchange in the brain (11,18). With much smaller pressure changes in the decompression phase, a similar but insignificant reverse trend was observed.

After reaching equilibrium following a step pressure change, there was no indication that the additional pressure caused an acceleration of the small deterioration expected as a result of time alone.

Although other authors (5,10) have stated that oxygen has a narcotic effect comparable with that of nitrogen, we could not confirm this; even though a slight reversible effect was seen in the 10-min exposures, it was not seen in the 20- and 120-min exposures. Ray and Hawgood (16) also failed to find the effect, although the late effects of acute oxygen toxicity caused a progressive loss of EP amplitude after between 60 and 100 min breathing 5.76 bar of oxygen. Their animals, like ours, were anesthetized. The possibility of the surrounding influences contributing to the effect in alert men or animals must again be considered as an alternative to an effect attributable to the gases breathed. For this reason, in the clinical area efforts are made to remove all extraneous influences when measuring CEPs (7,9). In compression experiments this is well nigh impossible.

The discrepency between our observations of no significant change in EP while breathing oxygen or oxyhelium at pressure, and the observations of others that a decrement occurs (5), although without any observable loss of performance, clearly supports Fowler and Ackles' doubts concerning EPs as measures of narcosis (6). However, these studies allowed us to provide a correction factor for the CEP measurements made under pressure during treatment experiments and indicated that this was not necessary for SEP measurements.

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The experiments reported herein were conducted according to the principles set forth in the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council, DHEW, Pub. No. (NIH) 78-23.

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REMOTE MONITORING OF NEURAXIAL FUNCTION IN ANESTHETIZED DOGS IN COMPRESSION CHAMBERS

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Spinal evoked potentials (SEPs) and cortical evoked potentials (CEPs) are being increasingly used experimentally, diagnostically and as a monitoring device in neurosurgical procedures (Grossman 1979). For proposed studies of the treatment of spinal cord decompression sickness, a system that would permit remote interrogation of the neuraxis and localization of lesions to major cord divisions was required.

Design constraints required that the model be controlled and maintained remotely in a pressurized chamber for periods of up to 5 h. The chamber containing an animal, once pressurized, could not be easily decompressed and opened without putting the experiment at risk; not even in the brief period when near atmospheric pressure, between the first dive and the treatment. In addition, the neuraxis and its integument could not be invaded, as such procedures might predispose to localized decompression sickness (DCS) (Kidd and Elliott 1975). The development of lesions resulting from decompression sickness is often rapid (Rivera 1964; Hallenbeck et al. 1975; Leitch 1979), so it was imperative that each interrogation and recording be short in order that onset times of decompression sickness be known within narrow limits, and the degree of severity be known before treatment.

The selected inputs were left and right peroneal nerves (usual roots in the dog L_6, L_7, S_1, S_2), left tenth or eleventh intercostal nerve, and left median nerve (usual roots C_8, T_1, T_2) (Hoerlein 1978). The evoked potentials (EPs) were recorded at segments L_1 or L_2, T_8 or T_9, C_7 or C_8, and at the right somatosensory cortex. This permitted localization to 5 broad regions: lumbar, caudal thoracic, rostral thoracic and caudal cervical cord, and the cortical and intervening regions. Experiments were conducted to determine a suitable anesthetic regimen and observe the effects of varying stimulus strengths.

Method

Conditioned male mongrel dogs weighing 9–20 kg were sedated with subcutaneous xylazine (2.2 mg/kg) and atropine (0.05 mg/kg) prior to being anesthetized intravenously with sodium pentobarbital or α-chloralose. The dogs were intubated and respiration was maintained with a Bird® Mark 7 ventilator using air. A catheter was placed in the left forepaw cephalic vein for anesthesia maintenance and infusions. Physiological monitoring of aortic and right ventricular pressures, EKG, EEG, rectal temperature, end-tidal gases, blood gases and acid-base status was carried out. Experiments were terminated by the intracardiac injection of saturated potassium chloride solution.

The dog was placed prone in a rigid head-holding stand (patterned after a stereotaxic frame), which incorporated a hot water plate. Rectal temperature was kept between 37.5 and 39.0°C. The skull was exposed by reflecting skin, muscle and periosteum over the right somatosensory cortex. A

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skin flap over the distal part of the nasal bones was also excised. Holes were drilled in the nasal bones and into the cancellous bone of the skull. The electrodes made from No. 4 stainless steel sheet metal screws were inserted. The cortical electrode was placed at a point one-third of the skull length, anterior to the inion and approximately 7 mm laterally. This was a point midway between the forelimb and hind limb regions of the sensorimotor cortex. Putting standard electrode gel into the drilled hole ensured an electrode impedance below 2 kΩ.

The reusable spinal electrodes were made from shortened stainless steel orthopedic finger wires (C-wires Concept Inc.) with a pin connector soldered to the cut end. The insulation consisted of 4 coats of clear polyurethane baked for 48 h at 110°C. Testing of the insulation revealed infinite resistance up to 500 V. Two millimeters of the tip were bared and the end was lightly sanded to allow easy passage through tissues.

The spinal electrodes were placed in a bipolar configuration. They were pushed into adjacent interspinous spaces in the plane of the spinal processes until they touched the posterior lamina in the midline. The electrodes were anchored by hammering them approximately 2 mm into the bone. Impedance was generally between 3 and 6 kΩ.

The stimulating electrodes were 20-gauge stainless steel needles on double banana pins secured with heat shrink plastic. The peroneal electrodes were introduced percutaneously so that they straddled the peroneal nerve where it was palpable over the neck of the fibula. The intercostal electrodes were placed one subcutaneously and one subcostally from the caudal side of the tenth or eleventh rib. Both these electrodes were secured to the skin by safety pins. The median nerve was stimulated at the point where it was palpable medially at the distal end of the humerus. The needles were laid subcutaneously over the nerve in an A-P direction with the cathode proximal. The arrangement was secured by taping the attached banana plug to the leg.

A Grass S88 stimulator and two Nicolet Computers of Average Transients (CAT) (Models 1074 and 1072) were driven by a Nicolet stimulus pulse generator (NIC-502). The 0.3 msec stimulus of 120 V (3 times motor threshold) at 10 mA was delivered through a Grass photoelectric stimulus isolation and constant current unit (PISU 6C) at a rate of 2.5/sec and directed through a 4-way switching box on the outside of the chamber. The output from all 4 EP sites was averaged simultaneously on the 2 CATs, the 3 SEPs by the 1074 with a 26–30 msec span and the CEP by the 1072 with a 110 msec span. For each recording 128 epochs were summed. The outputs were observed on 2 Tektronix oscilloscopes (5110) and recorded on 3 Hewlett-Packard X-Y plotters (HP 7045 A and B). On leaving the chamber the signals went to differential amplifiers (NIC-200A) (gain 10^4), before being further amplified (gain 40) and filtered on a 30–3000 Hz bandpass (NIC-501A). The EEG signal for the CEP was tapped between the amplifier and filter and presented simultaneously on a Tektronix oscilloscope (5103N) and after amplification by a Gould Universal amplifier, on a Gould chart recorder (Model 2800) with the other physiological outputs.

The EPs were recorded with the positive up convention and with a 2 msec delay before stimulation. The CEP records had 3 principal peaks ($P_1N_1P_2$) and up to 11 far-field potentials (FFPs) mostly observed before N_1 (Fig. 1). These FFPs were best seen in the median records.

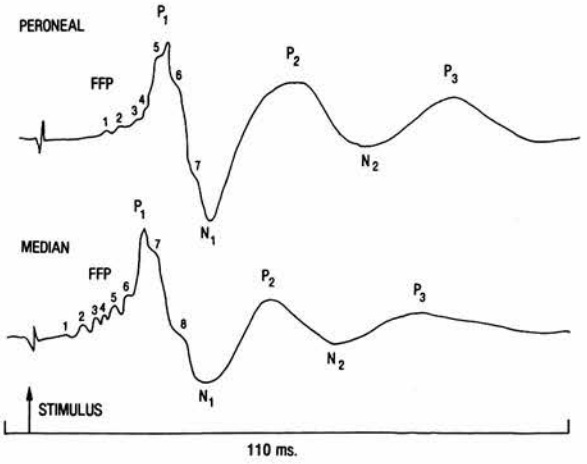

Fig. 1. Representative cortical evoked potentials. The principal cortical peaks are marked P_1N_1, etc., and the far-field potentials are marked 1–8.

The SEPs produced complex polyphasic wave forms with up to 10 easily identifiable pairs of peaks (Fig. 2). The more rostral to the stimulus was the recording, the longer the latency, the greater the spread, and the smaller the amplitude (Fig. 3). Records from close to the root input were dominated by a large negative wave and a later slow positive wave at 8–10 msec (Figs. 2, 3 and 4).

Analysis of these records took two forms. The CEPs were measured primarily for P_1N_1 amplitude. The OP_1 and N_1P_2 amplitudes were also measured as were the latencies of the primary peaks and the FFPs. Spinal evoked potential records were also measured for the principal peak-to-peak amplitude and for the amplitude of the late slow positive wave. Each trace was marked for

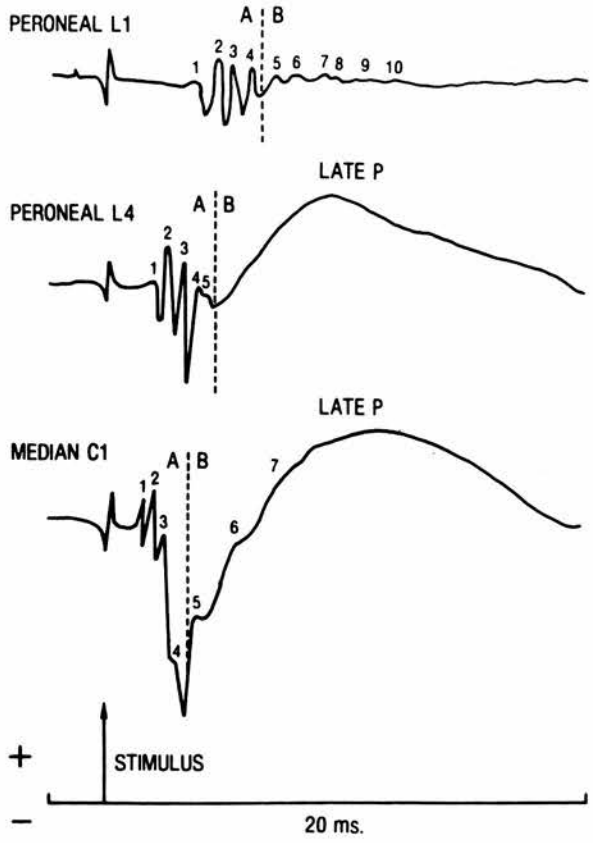

Fig. 2. Representative spinal evoked potentials. The records are labeled with stimulus and recording site. The numerals are placed by the positive peaks considered relevant. The succeeding negative peaks would have the same number.

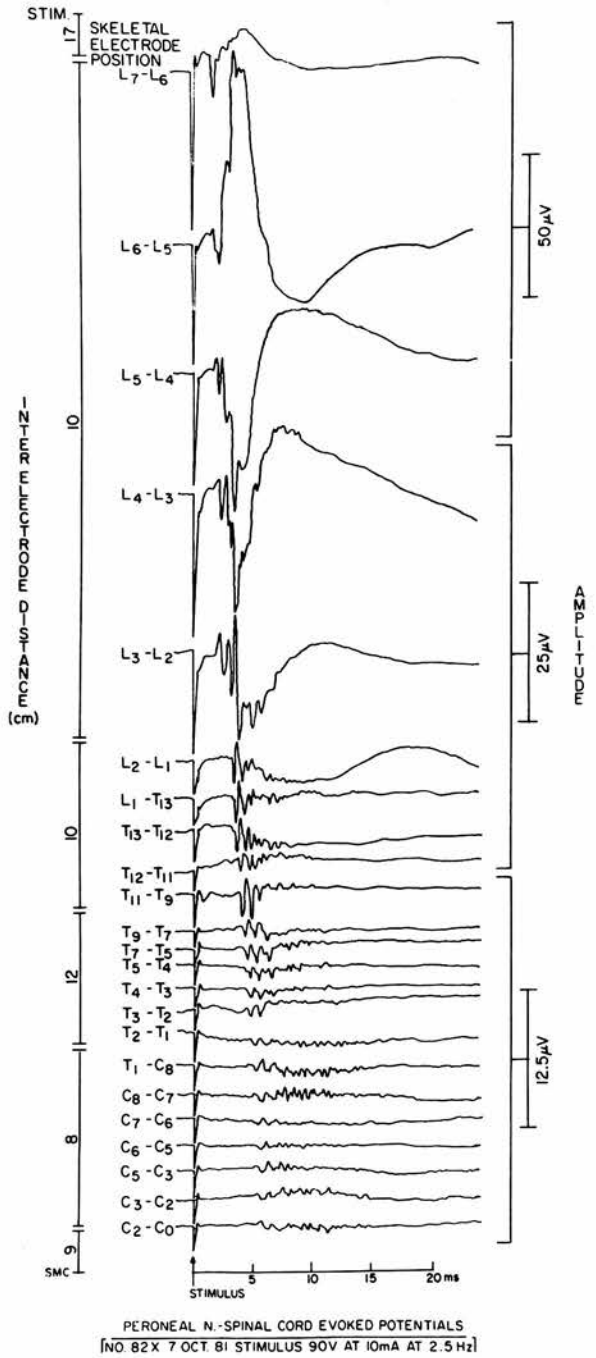

Fig. 3. Peroneal nerve-spinal cord evoked potentials. Sequential bipolar SEPs are shown from unilateral peroneal nerve stimulation at the neck of the fibula. Observe the large negative and late, slow positive waves that dominate the root entry zone. Latency and spread increase with distance from the stimulus, while amplitude decreases. The classical root entry zone recordings are inverted caudal to the root entry.

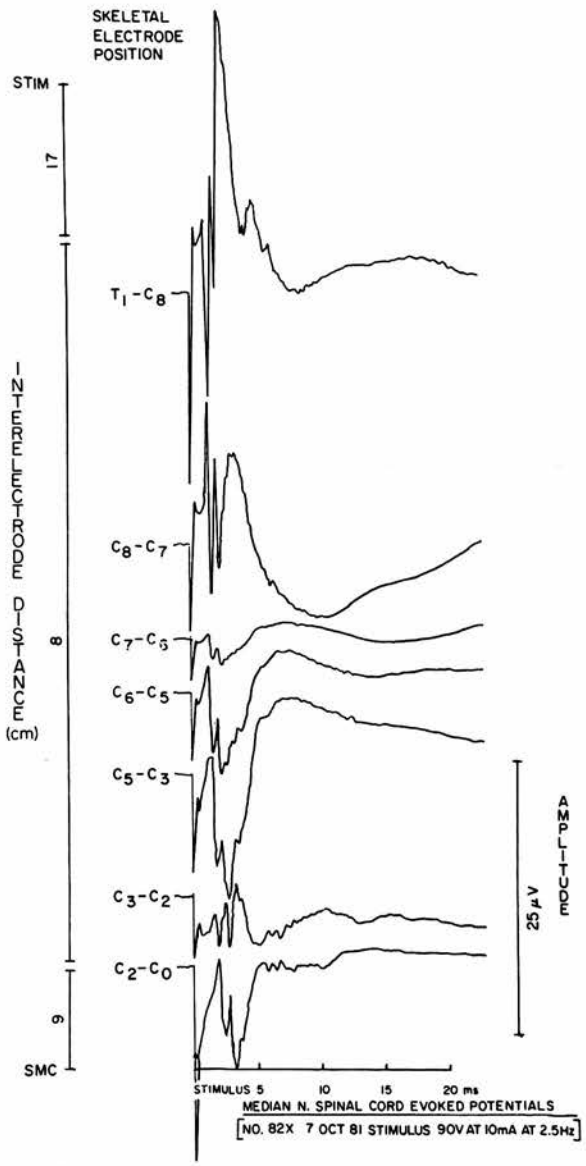

Fig. 4. Median nerve-spinal cord evoked potentials. Sequential bipolar SEPs are shown for unilateral median nerve stimulation at the distal end of the humerus. The SEPs show classical cord dorsum recordings for a root entry-zone evoked potential.

the peaks of interest and given an arbitrary baseline to compensate for occasional wandering slow voltage changes. They were then entered into a computer (PDP 11-70) using an Elographics digitizer (Model E241 with an Orthoplex Coordinator Sensor Type 3825-1). Latency change was of minor importance compared with amplitude, so peak-to-peak amplitudes were used for simple analysis.

The SEP waves fell into two types in each trace, large early waves, assumed to be of greater importance, and small later waves. These were arbitrarily separated for descriptive purposes and designated A and B respectively (Fig. 2).

Prior to this study the maintenance regimen for pentobarbital or α-chloralose anesthesia was guided by indications of a lightening plane of anesthesia. Any regimen which depended on shifting planes of anesthesia could well have a variable effect upon evoked potentials (Pimmel et al. 1976; Parker 1978a; Arezzo et al. 1979). Practical problems regarding anesthesia were the injection of large volumes of α-chloralose from outside a chamber pressurized to as much as 10 bar and the use of continuous infusion. Pentobarbital was chosen for the chamber studies because it could be injected in small quantities.

A retrospective analysis of the anesthetic regimens of 24 dogs showed that with an initial pentobarbital dose of 12.5 mg/kg (i.v.) the intervals for the maintenance dose of 25 mg varied between 1 and 155 min. Plotting the cumulative anesthesia given to each dog showed that the dose required in unit time was linear after about 40 min and was much less than the amount given during the first 40 min. The mean interval between doses after 40 min was 22 min. The dose-time slope was 4 mg/kg/h. To arrive at the 40 min point the initial dose was increased to 13.5 mg/kg and half that dose was repeated at 20 min. The maintenance dose was then given at 20 min intervals unless two successive 20 min checks failed to elicit a corneal reflex, then a dose was withheld. By the time the dog was placed in the chamber it was usually clear whether or not the maintenance dose should be changed.

Ten dogs were used to study the effect of stimulus voltage under each anesthetic regimen at the start of various experiments. Stimulus voltage was varied in 20 V steps between 20 and 140 V in either ascending or descending sequence. The CEP from the median nerve input was recorded. The latencies of P_1, N_1, P_2 and the peak-to-peak amplitudes were measured.

Median and peroneal CEP and SEP at the 3 cord sites were recorded in a further 7 dogs to see how SEP amplitude and CEP related under pentobarbital anesthesia.

Because the experiments leading to treatment of decompression sickness were likely to last about 5 h, it was important to know the stability of the preparation with regard to time. Six dogs were prepared and recordings of CEP and SEP were carried out at 20 min intervals over 5 h.

Fifteen dogs were used in the exploration of the use of evoked potentials in diagnosing and quantifying spinal cord lesions produced by decompression sickness. The dogs were prepared as described and placed in the compression chamber. The cephalic vein catheter was connected to a port in the chamber wall, through which pentobarbital and fluids could be given. Before diving, 4 sets of control EPs were collected for each of the 4 stimulus inputs.

Nine dogs participated in air dives to 230 ft for between 39 and 60 min, depending on their weight, and 7 dogs participated in air dives to 300 ft for between 10 and 17 min. After returning to the surface the functions of the left and right halves of the cord were studied alternately by stimulating the left or right peroneal nerves. This allowed observation of most of the length of the cord. A diagnosis of cord decompression sickness was made when the SEP changed. If the SEP changes were confined to the cervical electrodes, the median input was tested, and if confined to thoracic and cervical sites, then the intercostal and median inputs were tested. Usually changes were progressive, confirming the diagnosis. Treatment was deliberately delayed in order to prevent immediate complete recovery.

After a delay of approximately 17 min after diagnosis, treatment by recompression was begun. Eight dogs were treated with oxygen at 60 ft for 2 h and 7 dogs were treated at 165 ft breathing air for the 2 h. The magnitude of the SEP deficit was assessed on a final pretreatment recording of the first SEP site to show a change. Those inputs showing changes were measured at 5 min after arrival at pressure, at 15 min post arrival, and at 15 min intervals thereafter. The remaining inputs were measured at 0.5 h intervals. A simple numerical description of the SEPs was needed for statistical purposes. Pilot studies showed that fine discrimination techniques were not required for the gross changes that occurred. The SEPs were quantified by adding the peak-to-peak amplitudes ($P_1N_1 + N_1P_2 + P_2N_2$, etc.). All measurements made after the control period were expressed as a percent of the mean control values. The final pretreatment measurement was converted to indicate the amount of SEP amplitude lost. Cord lesions resulting from decompression sickness were both unpredictable and uncontrollable, therefore, it was desirable to apply a normalizing procedure. This was done by expressing all recovery as a percentage of what was lost.

Results

In comparing the effects of increasing stimulus voltage in dogs anesthetized with either pentobarbital or α-chloralose, it was shown that pentobarbital had a depressing effect upon CEP (Table I). The voltage of the 3 primary peaks was generally less than half that of the voltage in the α-chloralose dogs.

By 60–80 V the latency (Table II) was fixed under pentobarbital and the peak-to-peak amplitudes exceeded 90% of the maximum obtained at 140 V. Under both regimens the visible motor threshold was between 30 and 40 V, although CEP was clearly identifiable before them. A working voltage in which the response was asymptotic and the latency fixed was about 3 times motor threshold at 100–120 V.

In the 7 dogs in which the relationship between SEP and CEP was studied, amplitude grew proportionally in both SEP and CEP. The relationship was best between the early (3–5 msec) lumbar SEP waves designated 'A' and the peroneal CEP. The same applied for the comparable waves (1–4 msec) with the median-cervical SEP and CEP.

In the 5 dogs in which the effect of time on EPs was studied, no change in latency was seen. There was, however, a progressive fall in both cortical and spinal evoked potential mean amplitudes of between 1 and 2%/h and an increase in variance with time (Table III). In this group the direction of

TABLE I

Somatosensory cortical evoked potentials. Peak-to peak amplitude — effect of voltage and anesthesia.

Peaks	Condition	N = 10	Stimulus voltage							Amplitude in μV at 140 V
			20	40	60	80	100	120	140	
OP_1	PENTO	$\bar{x}$ (%)	6.6	60.0	81.6	90.1	91.2	97.2	100	39.2
		± 95%	−0.7–13.9	38.1–81.9	67.2–96.0	80.7–99.5	79.6–102.8	89.4–105.0	–	28.0–57.4
	CHLOR	$\bar{x}$ (%)	5.3	57.8	75.3	83.9	90.1	96.9	100	78.2
		±95%	−1.2–11.8	39.2–76.4	63.8–86.8	74.6–93.2	82.9–97.3	92.7–101.1	–	60.0–96.4
P_1N_1	PENTO	$\bar{x}$ (%)	4.4	56.8	87.5	91.5	96.8	98.9	100	72.7
		±95%	−0.3–9.1	36.6–77.0	74.3–100.7	85.6–97.4	89.8–103.8	94.1–103.7	–	40.7–104.7
	CHLOR	$\bar{x}$ (%)	4.7	55.5	74.1	82.7	91.0	96.5	100	170.1
		±95%	−1.4–10.8	38.7–72.3	62.7–85.5	72.9–92.5	84.2–97.8	91.6–101.4	–	116.0–224.2
N_1P_2	PENTO	$\bar{x}$ (%)	3.5	53.0	83.2	84.4	91.7	95.8	100	48.7
		±95%	0.6–6.4	30.6–75.4	67.3–99.1	76.4–92.4	82.2–101.2	90.4–101.2	–	29.4–68.0
	CHLOR	$\bar{x}$ (%)	3.9	58.4	81.1	87.0	96.1	98.0	100	137.0
		±95%	−1.2–9.0	42.2–75.6	65.0–97.2	73.1–100.9	83.2–109.0	91.2–104.8	–	71.6–202.4

PENTO = pentobarbital 4 mg/kg/h, bandpass 30–3000 Hz, nasal reference.
CHLOR = α-chloralose 40 mg/kg/h, bandpass 30–3000 Hz, nasal reference.

change of SEP and CEP P_1N_1 amplitude was observed, from both median and peroneal nerve stimulation, with regard to maintenance doses of pentobarbital. There was no clear indication that EPs decreased after anesthesia or increased during pre-anesthesia intervals. Only the late, slow positive wave at 8 msec in the median-cervical SEP showed a tendency to decrease after administration of pentobarbital ($P < 0.05$, chi-square).

Two examples of the EP changes in decompression sickness affecting the spinal cord are shown in Figs. 5 and 6. The first shows the diagnosis of a lesion in the lumbar region and the second that of a lesion in the thoraco-cervical region.

A common indication of imminent decompression sickness that would affect the cord was an

TABLE II

Somatosensory cortical evoked potential. Peak latency — effect of voltage and anesthesia.

Peak	Condition	N = 10	Stimulus voltage						
			20	40	60	80	100	120	140
P_1	PENTO	$\bar{x}$ (msec)	18.9	13.7	13.3	13.3	13.3	13.3	13.3
		±95%	15.1–22.7	12.4–15.0	12.5–14.1	12.5–14.1	12.3–14.3	12.3–14.3	12.3–14.3
	CHLOR (1)	$\bar{x}$ (msec)	15.0	14.4	14.1	13.8	13.7	13.6	13.6
		±95%	13.1–16.9	13.3–15.5	13.1–15.1	12.9–14.7	12.8–14.6	12.7–14.5	12.7–14.5
N_1	PENTO	$\bar{x}$ (msec)	32.1	21.6	20.3	20.0	20.0	19.9	20.0
		±95%	25.7–38.5	19.4–23.8	19.0–21.6	18.6–21.4	18.5–21.5	18.5–21.3	18.5–21.5
	CHLOR (1)	$\bar{x}$ (msec)	30.0	25.9	23.9	23.5	23.2	22.6	22.4
		±95%	25.4–34.6	22.6–29.2	21.1–26.7	20.9–26.1	20.5–25.9	20.3–24.9	20.1–24.7
P_2	PENTO	$\bar{x}$ (msec)	44.7	35.6	33.9	34.0	34.2	33.7	34.0
		±95%	40.2–49.2	32.8–38.4	31.3–36.5	31.3–36.7	31.6–36.8	31.1–36.3	30.7–37.3
	CHLOR (1)	$\bar{x}$ (msec)	53.3	45.4	43.8	43.4	43.4	43.4	43.0
		±95%	35.7–70.9	37.9–52.9	36.5–51.1	35.9–50.9	35.7–51.1	35.5–51.3	34.7–51.3

PENTO = pentobarbital 4 mg/kg/h, bandpass 30–3000 Hz, nasal reference.
CHLOR = α-chloralose 40 mg/kg/h, bandpass 30–3000 Hz, nasal reference.

TABLE III

Effect of time on evoked potentials (expressed as a percentage of control). N = 6, 2–6 measurements per dog, per period.

			Time period (h)					Overall	Range of amplitude μV (min) (max)
			0–1	1–2	2–3	3–4	4–5		
Peroneal	P_1N_1	$\bar{x}$	100.0	93.2	91.9	92.7	90.1	93.6	7
CEP		S.E.	5.9	5.2	5.7	6.3	8.7	6.9	108
Peroneal	N_1P_2	$\bar{x}$	100.0	97.6	91.9	88.3	92.8	94.5	7
CEP		S.E.	5.4	5.8	9.6	6.5	7.9	7.4	97
Lumbar	P_1N_1	$\bar{x}$	100.0	97.8	95.9	91.9	90.2	95.2	5
SEP		S.E.	2.1	3.7	5.4	5.0	5.6	5.0	101
Median	P_1N_1	$\bar{x}$	100.0	101.6	99.6	97.0	97.4	99.1	4
CEP		S.E.	2.7	5.3	6.3	6.9	8.6	6.0	74
Median	N_1P_2	$\bar{x}$	100.0	98.5	100.2	96.6	96.0	98.3	1
CEP		S.E.	4.1	5.7	6.0	7.7	7.2	6.3	38
Cervical	P_1N_1	$\bar{x}$	100.0	97.0	94.2	92.5	94.6	95.7	3
SEP		S.E.	1.4	2.7	2.6	3.0	3.1	2.9	53
Cervical	Late	$\bar{x}$	100.0	95.8	95.2	94.5	91.9	95.5	3
SEP	P	S.E.	2.2	3.9	4.3	5.8	5.4	4.5	113

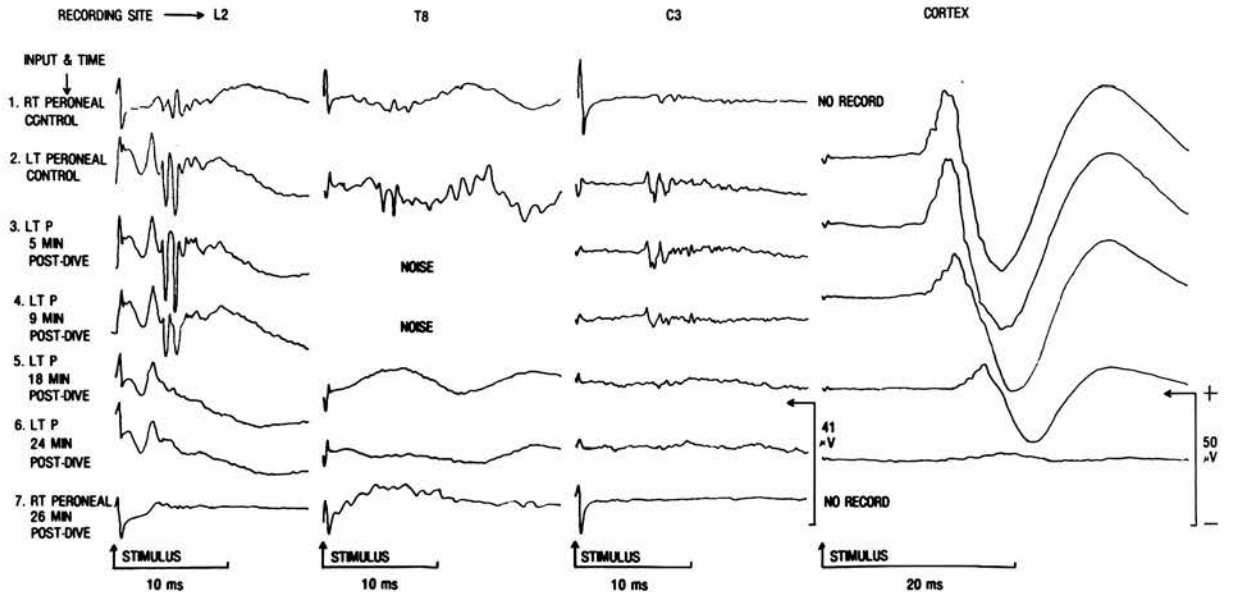

Fig. 5. Decompression sickness of the lumbar-caudal thoracic spinal cord. An illustration of the sequence of EP recordings leading to the diagnosis of DCS. Record 3 shows an occasional prodromal sign of DCS with some increase in amplitude associated with wave form changes in the later peaks. The thoracic record was destroyed by noise, another prodromal sign. The CEP shows no sign of change. Record 4 shows clear changes at all sites, beginning in the lumbar region. Checks of intercostal and median inputs revealed no changes which localizes the lesion to below T_8. The remaining records show the progressive failure of conduction with time.

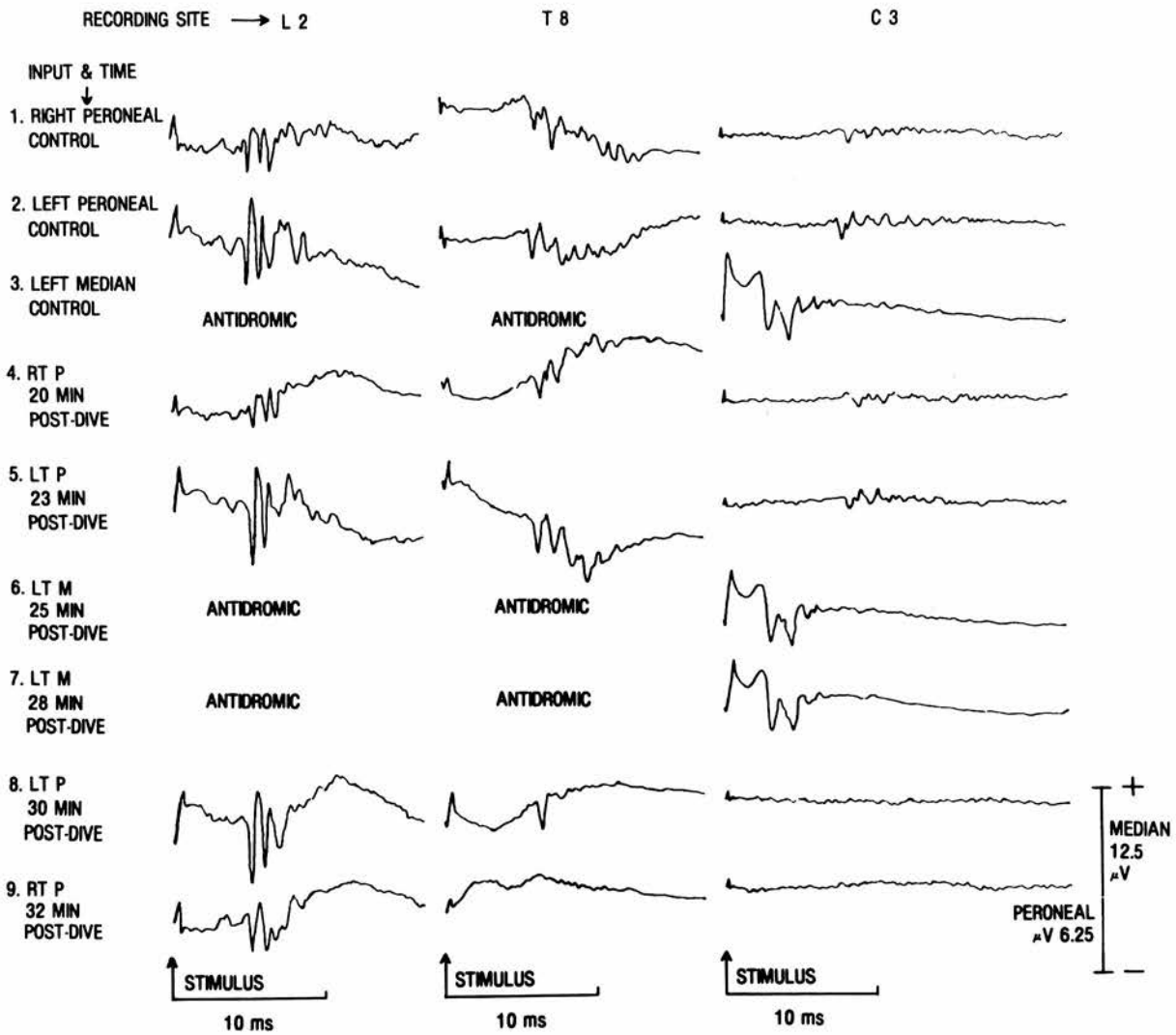

Fig. 6. Decompression sickness of the thoraco-cervical spinal cord. The large sweeping records of the antidromic EPs from the median nerve are not shown. Record 4 shows the earliest indication of change with a latency shift in the cervical record. A possible change in the later peaks of the lumbar record may also be relevant. Similar changes are evident in record 5. Records 6 and 7 of the median-cervical EP show a progressive loss of the later waves and some changes in the earlier peaks. The final two records show some lumbar involvement and the failure of any transmission through the thoracic region. No cortical records are shown because early postdive cerebral DCS developed, obliterating much of the CEP and most of the FFPs.

outbreak of high-frequency, high-voltage noise in the thoracic electrodes. It was possible to suppress this electrical activity using pancuronium bromide, which suggests a myogenic origin. Occasionally the noise was just signal breakup similar to a series of cardiogenic artifacts.

Experience showed that looking for small changes was futile because they were hard to distinguish from normal variation. Generally, if small changes were due to decompression sickness, they would develop into significant changes. Fig. 7 illustrates a bilateral loss of peroneal-lumbar SEP, which was first observed on the right side. The apparent loss before diagnosis is an artifact result-

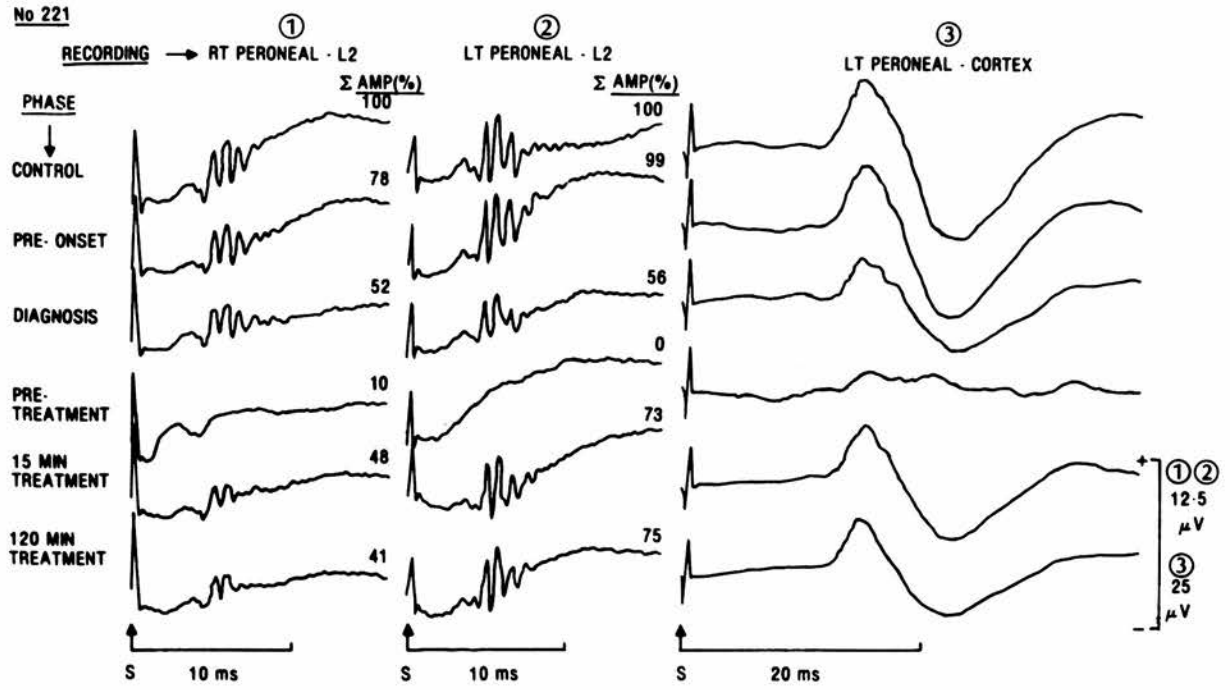

Fig. 7. Decompression sickness of the bilateral peroneal-lumbar cord. The numbers under Σ AMP (%) indicate the summed peak-to-peak amplitude as a percent of control. The SEP change was first seen in the right peroneal input. The apparent low pre-onset value for Σ AMP (%) was present after the start of the first dive and may therefore be considered an artifact. The left peroneal-lumbar SEP lost all wave form before treatment. Because the duration of the lesion was shorter than that of the right peroneal-lumbar lesion, however, it showed a better recovery in treatment.

TABLE IV

SEP loss in decompression sickness and recovery with treatment *.

		60 ft oxygen	165 ft air
n		8	7
Delay (min)		16.7 ± 4.4	17.2 ± 3.7
Loss ** (% of control)		60.6 ± 22.4	64.1 ± 16.9
Recovery ***	15 min	25.1 ± 23.4	16.7 ± 22.9
(% of loss)	40 min	28.4 ± 37.0	20.6 ± 20.9
	80 min	33.9 ± 33.3	22.3 ± 19.7
	120 min	24.8 ± 28.8	24.7 ± 18.6

* The values are $\bar{x} \pm$ S.D.

** The SEP loss is expressed as a percent of the mean control value.

*** The recovery results are the ratio of SEP recovery to SEP lost expressed as a percent.

ing from a step change in amplitude that occurred during the first dive. There was a better return in the lesion of shorter duration on the left side than in the lesion of longer duration on the right side.

The onset of SEP changes after return to the surface varied between 2 and 38 min in the 15 dogs. By the time treatment was begun, both groups had a similar loss of SEP of about 60% in the primary site (Table IV). Most lesions occurred in the lumbar and lower thoracic cord with an occasional cervical lesion. During treatment most recovery occurred within 15 min. There was no difference between the two treatments after 120 min; each recovered approximately 25% of the lost SEP.

Occasional dogs developed brain-stem lesions.

These could be identified in dogs with normal SEPs and apparently normal EEGs, but abnormal CEPs with varying numbers of missing FFPs.

Discussion

The effects of chloralose and pentobarbital on CEP revealed a considerable depression in amplitude attributable to pentobarbital. Because the comparison did not include unanesthetized animals, it is impossible to comment on how CEP or SEPs deviated from normal. In comparing these two anesthetics, Harding et al. (1979) observed that pentobarbital reduced the number of active cortical neurons when compared with choralose. It has also been observed that barbiturate anesthesia in low doses tends to facilitate CEP but that higher (surgical anesthesia level) doses tend to depress CEP (Pimmel et al. 1976; Dafny 1978; Nordwall et al. 1979). Dafny attributes this to an effect upon the reticular activating system. Abrahamian et al. (1963) also point to an extralemniscal influence but on the later waves. Other authors observed that in general only the late non-specific parts of the CEP were depressed (Clark and Rosner 1973; Allison et al. 1963). These slightly conflicting observations may result from the maintenance of different levels of anesthesia and the fact that all those observations, that suggested that the early waves (< 100 msec) were unaffected, were made in man. The tentative observation that the late positive wave in the SEP recorded close to the root of entry might be affected by anesthesia may be supported by Robson's (1971) observation that presynaptic inhibition is potentiated by barbiturates leading to monosynaptic reflex depression. No dogs in the chloralose experiments were prepared for SEP measurement. It seems probable, however, that relative to the unanesthetized state and to chloralose anesthesia, the SEPs were also depressed by pentobarbital as seen by Nordwall et al. (1979). Rosner and Clark (1973) observed that pentobarbital caused a reduction in excitatory activity in cord and suppression of transmission in small fibers (cutaneous receptive field) in the anterolateral columns at moderate doses. These findings are all largely in accord with those of Albe-Fessard et al. (1970) who compared these two anesthetic agents.

The bipolar cord electrode configuration with the electrodes embedded in bone close to the spinal cord produced relatively noise-free SEPs, with a useful amplitude and sufficient detail to enable early changes to be detected in decompression sickness. This was preferable to the larger amplitude but less detailed SEP obtained with monopolar electrodes by others (Cracco 1973; Ertekin 1978). Sarnowski et al. (1975) and Ertekin (1978) similarly observed that SEP amplitude and definition improved with the proximity of the electrode to the cord.

The first 3 primary cortical waves, P_1, N_1 and P_2, were monitored to the exclusion of the later waves, which were more variable. The observed mean latencies in a comparable group of 11 from the median nerve were 10.2, 15.9 and 26.8 msec respectively and from the peroneal nerve 14.0, 20.9 and 31.8 msec respectively. These CEPs are comparable with those observed in dogs by Norrsell (1966) and Parker (1978a, b). Norrsell, in cord transection experiments, showed that the P_1N_1 components were transmitted ipsilaterally in the dorsal columns and in the dorsal part of the lateral funiculus. He also observed that waves with the latencies of P_2 and later were transmitted through both ipsilateral and contralateral ventral funiculi.

While remembering that species differences exist in the neuroanatomy (Arezzo et al. 1979), similar findings were reported by Simpson et al. (1981) in monkeys. Large diameter fibers in the dorsal columns contributed to waves of latency less than 40 msec and small diameter fibers in the anterolateral columns contributed to latencies greater than 70 msec. The waves between 35 and 70 msec (P_2N_2) had a dual contribution from both columns. These findings are generally supported by human work which shows that cord lesions which cause the greatest reduction in the early CEP waves are associated with impairment of vibration and position sense while the impairment of the $P_2N_2P_3$ waves is associated with loss of pain and temperature sense (Sances et al. 1978; Yamada et al. 1978).

Between 4 and 7 FFPs were commonly observed in the CEP; the majority preceded N_1. They

could be observed bilaterally with a unilateral stimulus. They were most pronounced with median nerve stimulation, which showed as many as 11 FFPs. The earliest observed was the stationary wave closest to the stimulus which was sometimes also seen in the SEP and is attributed to the entry of the dorsal root to the cord. We failed to find any descriptions of FFPs in dogs in the literature, and as we did not investigate their origin in the dog any inferences regarding their site of origin remain speculative. The fixed nature of their latency indicates that they are volume conducted potentials arising from events fixed anatomically.

Wiederholt and Iragui-Madoz (1977) observed 4 FFPs on the rising slope of P_1 in rats. They attributed them in sequence to dorsal column, dorsal column nucleus and medial lemniscus, ventral posterior thalamic nucleus and sensory radiation and possibly also cerebellar pathways and cerebellum. Using cats allowed a better separation of the FFPs, and they were localized to dorsal column, dorsal column nucleus and/or medial lemniscus, cerebellum and/or cerebellar pathways, ventral posterior nucleus of thalamus, and sensory radiation with some thalamic contribution (Wiederholt and Iragui-Madoz 1977). Human work has produced similar observations but with more complexity, including observation of the peripheral nerve or dorsal root (Cracco and Cracco 1976; Anziska and Cracco 1980; Desmedt and Cheron 1980; Pratt and Starr 1981). Future work may produce more detailed knowledge of these origins as clearly, if we can see up to 11 FFPs; those smaller numbers reported by other authors may be broken into more separate peaks.

The number of axonal volleys observed with this preparation probably reflects the supramaximal stimulation of a distant peripheral nerve allowing time for separation of synchronous volleys in axons of different sizes and, therefore, different conduction velocities (Figs. 3 and 4). The similarity of the root entry segment potentials recorded by Bernhard (1953) from the cord dorsum and these records suggests that they are basically those that might be recorded from the cord dorsum, although the activity seen is not necessarily confined to the dorsal columns. Others using similar electrode placings but with monopolar recordings found less complex wave forms than these (Holliday et al. 1979; Nordwall et al. 1979).

It was observed that as the recording site moved rostrally, additional peaks separated from those evident around the entry segment (Figs. 3 and 4). These progressively lost amplitude and increased in latency with a wider separation of peaks as the distance increased. It is assumed that the loss of amplitude is the result of the giving off of collaterals so that neuronal bulk is reduced, and that the apparently different conduction velocities represent axons of different sizes or synaptic activity (Sarnowski et al. 1975). It would be fair to assume that the variation in axonal size is a continuum. Therefore, in order to account for the clear separation of peaks, it must be assumed that different groups of similar sized axons are synchronous and are perhaps grouped by modality, these need not be discretely separated anatomically. It was not possible to correlate different SEP peaks with cortical FFPs or with a particular anatomical position in the cord, but it may be presumed that the earlier and larger peaks contribute most to the CEP and, therefore, are mainly in the dorsal column. Certainly the late peaks may be lost in decompression sickness without apparent change in the CEP, and the early peaks must change in order for CEP to change.

In dogs, dorsal column potentials recorded from light touch, hair, joint movement and deep pressure can also be produced by electrical stimulation. The physical stimuli cannot be detected in the anterolateral columns (spinothalamic) although electrical stimulation produces a response commensurate with $A\beta$ and $A\delta$ fibers, the so-called 'fast-pain fibers' (Illingworth and Molina-Negro 1974). Shimoji and Kano (1975) recording epidurally in man found that moving from the posterior to the anterior space simply inverted the potentials recorded dorsally, which suggests that all cord activity can be observed from the cord dorsum.

Clinical and experimental experience suggests that the use of SEP and CEP has considerable potential in predicting outcome and in monitoring cases of acute cord injury (Nash et al. 1977; Parker 1978b; Rowed et al. 1978).

These initial efforts to develop the evoked potential technique to monitor the occurrence and

treatment of spinal cord decompression sickness proved effective in allowing diagnosis and a degree of localization of the lesions, without invasion of the spinal canal and neuraxis. The two treatments used to test the model were similar to clinical treatments in current use. Therefore, it was not surprising that the recoveries should be similar. The delay of approximately 17 min was sufficient to prevent complete recovery. The observation of cortical FFPs was a useful adjunct to the method. It enabled differentiation between brain-stem lesions and lesions rostral or caudal to the brain-stem.

The simple method of summing peak-to-peak amplitudes gave an adequate description of the SEP changes seen in decompression sickness and its subsequent treatment. There appeared to be no reason to use the fine discrimination techniques described by John (1974) and Dill et al. (1976). The development of this model will permit for the first time a proper study of the relative merits of pressure and oxygen in treating spinal cord decompression sickness.

Summary

This paper describes the development of an electrophysiological model using spinal and cortical evoked potentials (SEP, CEP), for the diagnosis and monitoring of spinal cord decompression sickness (DCS) in anesthetized dogs. A comparison of α-chloralose with sodium pentobarbital showed that the latter caused a reduction in CEP amplitude. Continuous observation of EPs over 5 h showed a small reduction and an increasing variance of amplitude with time. The effectiveness of the method in the diagnosis of DCS and in studies of the adequacy of treatment is illustrated with several examples.

Résumé

Exploration fonctionnelle à distance du névraxe chez le chien anesthésié en chambre de compression

La mise au point d'un modèle électrophysiologique applicable au chien pour le diagnostic et la surveillance à distance du traitement des accidents de décompression touchant la moelle épinière est décrit. Des potentiels évoqués spinaux (PES) et corticaux (PEC) par stimulation des nerfs médian, intercostal et des deux nerfs périnéaux ont été enregistrés au niveau lombaire, thoracique, cervical et cortical. Une comparaison des effets sur le PEC, de l'alpha-chloralose et du pentobarbital sodique a montré que ce dernier diminue leur amplitude.

L'enregistrement en continu pendant 5 h des PES a montré une légère diminution de l'amplitude et une augmentation de sa variance au cours du temps. Des exemples d'utilisation sous pression de cette méthode pour l'exploration des accidents de décompression touchant la moelle épinière sont présentés.

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